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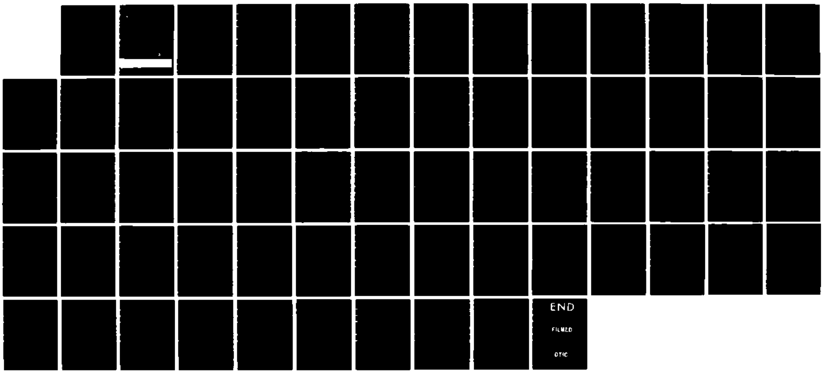

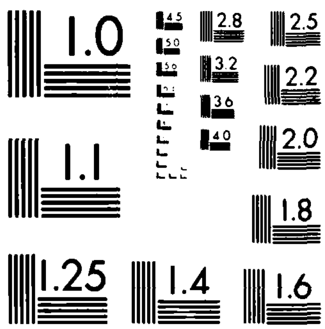

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Technical Report: NAVTRAEQUIPCEN IH-356

AD-A158 773

VISUAL DISPLAY PARAMETERS

Richard C. Hebb
Simulation Technology Branch
Naval Training Equipment Center

Final Report, Oct 1982 to Sept 1984

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This report covers work performed under NACTRAEQUIPCEN Project 3774, Visual Display Parameters (VDP). The VDP project was directed towards the analysis of wide-angle visual displays on dome (or spherical) screens. The objective was to gain the capability to explore the image parameters of distortion, luminance, and resolution of proposed dome displays. A problem with dome displays is in their physical specification and subsequent display performance. Often, the resulting display system does not meet the intended specifications. The main product of the VDP project is a FORTRAN computer program, NVDPMAP, that assists in the analysis of a dome display based on a generalized projection system model. The purpose of the program is to reduce the time spent performing calculations, to automate and improve display analyses, and to provide graphic output concerning a system's performance in an easily digestable form. The parameters of distortion, luminance, and resolution can be examined on perspective and aitoff maps of the display. NVDPMAP can be run via a command sequence menu, which also contains other programs developed under this

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19. ABSTRACT (cont'd)- project. Input to NVDPMAP may be from a formatted input file, or may be entered interactively when running the program. The NVDPMAP program is an aid in designing a dome display and predicting final performance. The basic NVDPMAP program can be modified to change the projector, lens, and screen functions to those of a specific projection system.

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1.0 INTRODUCTION

1.1 Visual Display Parameters Project

This report covers work performed under NAVTRAEQUIPCEN Project 3774, Visual Display Parameters (VDP). The objective of this work was the exploration of the image parameters in dome (or spherical) display systems. Work was concentrated on providing analysis tools for prediction of distortion, luminance, and resolution performance in dome displays. The effort resulted in the development of a set of FORTRAN programs for use in evaluating the performance of wide-angle, multi-projector dome visual systems.

The main product of the VDP project is a FORTRAN program, NVDPMAP, that assists in the analysis of dome displays based on a generalized projection system model. (see section 2.2 and Appendix A) The projection model is used to find the theoretical distortion, luminance, and resolution of the imagery provided to a viewer by the projection system. The model includes the ability to define the location, orientation, and characteristics of a number of projectors within a dome screen, the screen luminance characteristics, and the location of the design viewpoint. The projector characteristics that can be defined include each projectors': light and resolution output, projection lens mapping, lens f/#, lens focal length, optical axis orientation, and projected field of view. Options are available to select one or all of the anaylsis functions offered by NVDPMAP.

In the projection model, a crosshatch pattern is theoretically projected from each projector for a test pattern. The projection of each crosshatch onto the screen covers an image display area on the screen defined as a view window. Outputs from the program are in the form of perspective and aitoff maps of the view windows, with optional table outputs. The perspective maps give a perspective view of one projector's crosshatch pattern from the viewpoint. The aitoff maps show the relative arrangement of all view windows within the spherical viewing volume surrounding the viewpoint.

More programs were written for the VDP project to assist in measuring a dome screen, verifying program outputs, finding raster shapes for distortion correction, and to help find inputs for the main analysis program. These programs are briefly discussed in this report, and additional information on the raster shaping program is available in reference 1.

The VDP programs are resident on the VAX 11/780 #1 located in the System and Computer Technology Division (Code 74) of NAVTRAEQUIPCEN. All programs are written in FORTRAN IV Plus and are located in subdirectory [N731RH.MENU]. Graphic outputs are provided on a Textronix graphic terminal

(1) NAVTRAEQUIPCEN Technical Report IH-332 'Computer Program for Analysis of Spherical Screen Distortions', March 1982

model 4014-1. The process for running the programs is simplified by the use of a command procedure providing menu operation of the programs. To assist in use of the menu, a help option on each menu item is included in the menu.

A VAX user account is required to gain access to the VDP programs. To use the program menu, the assignment ' VDP:=@[N731RH.MENU]MENU.COM ' should be included in the user's system LOGIN.COM file to define VDP during login. The menu can then be accessed by entering 'VDP<CR>' after the login file is initialized.

1.1.1 Wide Angle Display Systems - The VDP project was directed towards the analysis of wide-angle real image visual displays. A wide-angle display may be defined as a display that fills a horizontal FOV approaching 180 degrees, or more, at the viewpoint. A real image is formed on a surface (or screen) as opposed to a virtual image which is formed in space. A real image can be viewed without any additional viewing aid, while a virtual image usually requires additional viewing optics.

To obtain a horizontal FOV of 180 degrees or more, curved screens (domes or cylinders) are used to overcome the 180 degree limitaion of flat screens. In a wide-angle display, several projectors are used to project imagery onto different areas of the dome screen surface to provide the Total Field of View (TFOV) desired. The use of several projectors removes the 180 degree projection limitations of conventional projector lenses and their flat image surfaces.

A typical wide-angle display may have three projectors with Projected Fields Of View (PFOV) measuring 70 degrees vertical by 90 degrees horizontal. When properly positioned these three projectors could provide a continuous TFOV of 70 degrees vertical by 270 degrees horizontal, but in practice the horizontal field may be smaller due to overlapping of the view windows. Each projector would be provided imagery from a Computer Image Generator (CIG) that corresponds to the scenes for that projector's view window orientation relative to the viewpoint. With the CIG providing perspectively correlated imagery of a mathematically modelled landscape to each projector, a viewer is provided with a large FOV that gives an increased visual interpretation of motion compared to narrow field imagery.

Wide-angle display systems are often required for the visual subsystem of jet aircraft and helicopter flight simulators to provide the FOV required for proper training. Wide-angle displays are needed when training pilots to carry out Nap of the Earth (NOE), ground attack, air to air combat, and other missions requiring critical maneuvering and visual tracking.

1.1.2 Dome Display Analysis Problems - One problem with multi-projector wide-angle displays is in their physical specification and subsequent display performance. Evaluating the performance of several projectors located within a dome screen is not a simple task, and the process is time consuming. Many calculations are required and the tabulation of the results is tedious and difficult to interpret.

The curved screen surface introduces many problems connected with distortion of imagery intended to be perspectively viewed. When the performance of the system is examined, the curved screen can cause problems due to changes in the angle between the projected ray and the screen surface normal at every image point. These changes affect the relative gain of the screen for the projected image rays, which then affects the luminance. Additionally, the luminance is affected by changes in the throw distance (distance from the projector to the screen surface), which is not a simple function of the projection angle from the lens optic axis, as is the case for flat screens. In a dome screen, the throw distance depends on the dome radius, projector location and orientation relative to the dome origin, and the spherical angles of projection for each image ray. These same problems exist for resolution calculations in a dome display. For every pixel projected onto the screen, the projection distance varies as above. Changes in the angle of intersection with the screen surface can change the perspective size of a pixel dramatically, complicating resolution calculations.

Another problem in dome displays are the image variations between view windows when butting or overlapping several view windows together to form one continuous image. Any abrupt image change across view window seams will be noticeable and could affect training. The need is to determine the performance of the combined components of the wide-angle projection system before actual construction. If the constructed display does not meet the minimum visual specifications, then its training function would not be met, and millions of dollars could be wasted.

The purpose of the programs to be discussed in this report is to reduce the time spent performing calculations, to improve the quality of the analysis, and to provide graphic output concerning a system's performance in an easily digestible form. The purpose is met by the definition of a generalized dome projection system model which may have up to six projectors. The program uses this model to calculate the systems' performance in the areas of distortion, luminance, and resolution. The programmed calculations greatly speed up the analysis task and the graphic outputs are a convenient method of tabulating the system performances in visual form for quick interpretation of system performance.

2.0 VISUAL DISPLAY THEORY

2.1 Basic Analysis Process

The name of the display analysis program is NVDPMAP. The key process that takes place in the NVDPMAP program is the theoretical projection of a crosshatch test pattern onto a screen, followed by a mapping of the test pattern back to the viewpoint.

The croshatch test pattern is projected onto the dome screen by each projector defined in the system. The crosshatch image area on the screen defines the projector's view window. The pattern is then perspectively mapped onto a view plane in front of the viewpoint. (see figure 2.2-1 below)

Perspective maps of each crosshatch are drawn on a Textronix graphic terminal to give a proper perspective view of the crosshatch. The perspective is from the specified viewpoint for the viewing axis aligned with the crosshatch center. Successive perspective maps are drawn that show: (1) the distortion percentages (IRE definition) at the crosshatch corners and at the midpoints of the four bounding edges of the crosshatch, (2) percentage luminance variations across the projected image using contouring, and (3) pixel resolution values in arc minutes by use of contouring. A contouring subroutine, NCONTOUR, linearly interpolates the location of points within the crosshatch that have equal luminance or resolution values. Each perspective map is labelled with the projector description, the type of analysis (luminance or resolution), and the minimum and maximum values for the parameter analyzed.

After all perspective maps selected have been drawn, optional aitoff maps of the entire projection system are drawn on the graphic terminal. The aitoff maps are used to show the angular location of the outlines of each view window relative to the other projected view windows. These window outlines are drawn on the aitoff map relative to the viewpoint position. The aitoff maps provide an excellent method for evaluating the total system performances across the Total Field Of View (TFOV) provided by the combination of projectors. On the aitoff map, the gap or overlap between the view windows can be easily seen and the TFOV provided can be determined.

Additional information that can be shown on the aitoff maps are the percentage luminance contours and the pixel resolution contours of each view window. These luminance and resolution contours on the aitoff map provide a means of finding the locations of maximum and minimum luminance and resolution for the entire projection system, and the variations of luminance and resolution across adjacent view windows. The aitoff maps are labelled with the entire projection system description, the type of analysis performed, and the minimum and maximum values of the parameter analyzed for all projector view windows.

2.2 Projection System Model

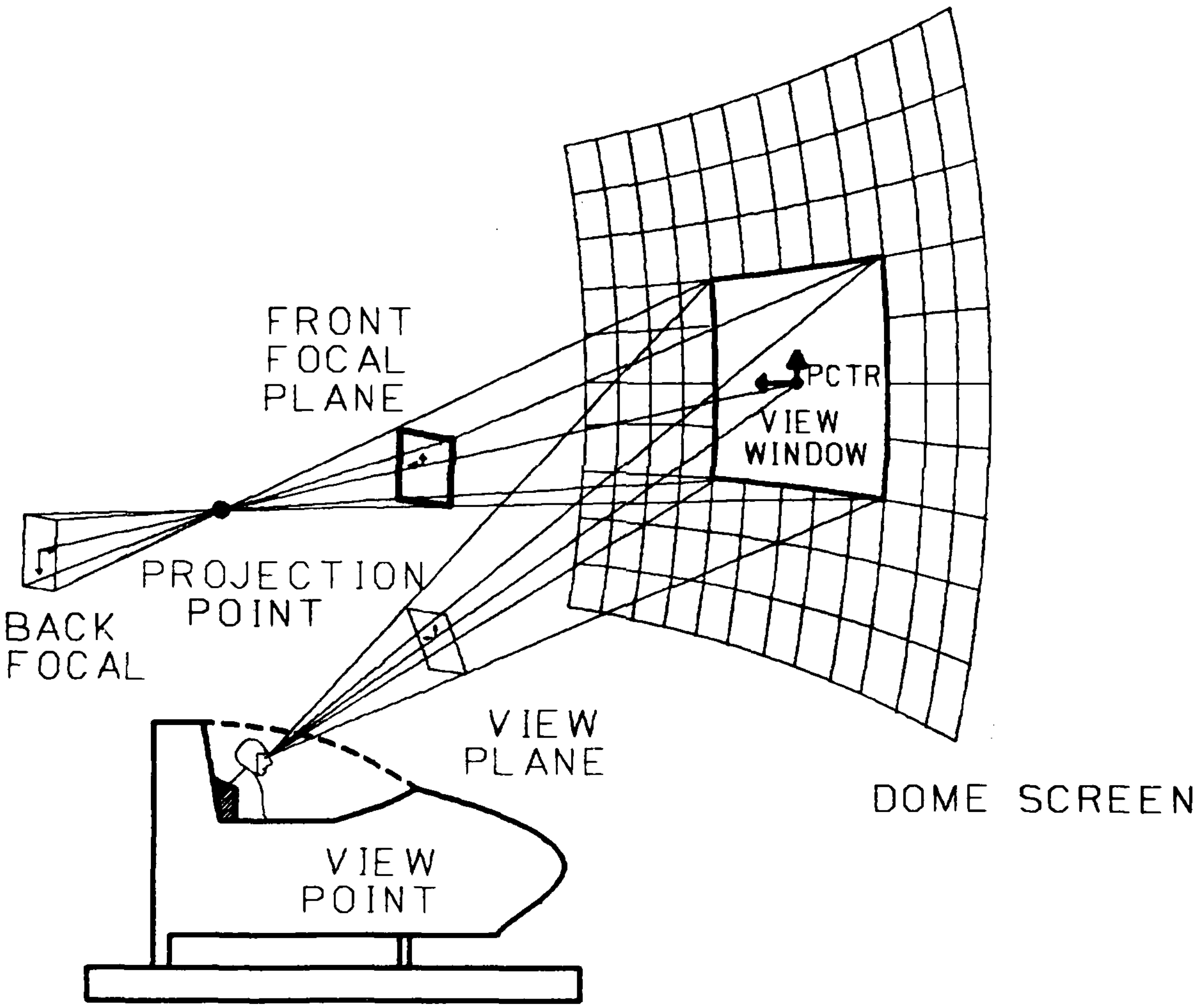


Figure 2.2-1 NVDPMAP Projection System Model

Figure 2.2-1 shows the key components of the projection system model. Starting at the left side of the figure on the lens Back Focal Plane (BFP, also called the target plane of the projector), object points pass through the projection lens to an imaginary Front Focal Plane (FFP) and onto the screen surface. This follows the process of projecting the object from the target plane to the screen. The area of imagery on the screen is called the view window, and is centered at the location labelled PCTR. PCTR is the intersection point of the projector optical axis with the screen. Continuing on to the viewpoint, image points on the view window are perspectively mapped onto the view plane to provide the graphic output of the view window image as seen from the viewpoint. The view window image coordinates are 3-D, while the view plane image coordinates are 2-D.

In the NVDPMAP program, the following parameters can be set in the projection system model to describe the projection system:

- Projector System Name, LABEL
- Projection Screen Radius, R
- Screen Gain and Type, Gmax & Gtype
- Viewpoint, EN (XE,YE,ZE)
- # of Projectors (up to 6), NP

and, for each projector:

- Projection Point, EX (XP,YP,ZP)
- View Window Center, PCTR (PXCTR,PYCTR,PZCTR)
- # of Crosshatch Lines, NVERT & NHORIZ
- Projected Angular Size of Crosshatch, VPFOV & HPFOV
- # of Lines and Pixels on Video Raster, LINES & PIXELS
- Lens Focal Length, f/#, and Transmission F, FNUM, & T
- Lens Light Output, Fmax & LCODE

These parameters, and several program output selectors, are entered into NVDPMAP in one of two ways: by specifying a specially formatted data file, or from the keyboard in response to program prompts. The use of the formatted input file is recommended to reduce input error, and, more importantly, to create a record of the system description. This input file format is given in appendix A, along with a description of each input parameter and its units.

2.2.1 Projection Geometry - The 3-D locations of the projector (EX), viewpoint (EN), and view window center (PCTR) in the projection system are specified relative to the origin of the dome screen. EN, EX, and PCTR are located by their 3-D coordinate displacement from this dome center reference. PCTR is used with EX to determine a projector's optical axis orientation. Three 3-D coordinate systems exist within the program, one each at the dome center, viewpoint and projector, however, the only 3-D coordinates specified by the user are those referenced to the dome center.

Note that all 3-D coordinates should be given in inches relative to the dome origin.

The following coordinate and angular conventions are used within the programs. The 3-D coordinate systems are right handed systems with the Z-axis up, the Y-axis to the left, and the positive X-axis is defined to be the reference axis. All spherical angles are referenced to the X-axis, which is defined as the zero degrees vertical and zero degrees horizontal, (0V,0H), direction. In a flight simulator, the X-axis would correspond to the forward axis of the aircraft. Vertical spherical angles are horizon referenced (X-Y plane) with positive angles above the horizon and negative below the horizon. The horizontal spherical angles, relative to the X-Z plane, are positive to the left (counter-clockwise direction, X into Y) and negative to the right (clockwise, X into -Y).

2.2.2 Projection Test Pattern - The test pattern used in the analysis is a variable crosshatch which is specified by the user. The number of vertical lines and horizontal lines are specified when running NVDPMAP by entering an integer for the variables NHORIZ and NVERT. NHORIZ specifies the number of horizontal points, and NVERT specifies the number of vertical points in the crosshatch. Rather than specifying the physical size of the crosshatch pattern on the projector object plane, the user enters the Projected Fields of View (PFOV), both horizontal - HPFOV and vertical - VPFOV, for the pattern. NVDPMAP combines the PFOV's with the lens focal length and mapping type, and then automatically calculates the required size of the crosshatch that is placed on the BFP of the lens.

There are two basic limitations for the crosshatch. One is that the total number of points on the crosshatch (at the intersections of each vertical and horizontal line) is limited by the dimension of the variable arrays. This dimension is 1000 points, and the total number of points can be calculated by multiplying NHORIZ AND NVERT. A 30 by 30 crosshatch would be allowed, as well as a 40 by 25, but a 35 by 35 crosshatch would exceed the storage capacity of the variable arrays. Typically, an 11 by 11 crosshatch will provide enough points for an analysis.

The second limitation for the crosshatch concerns the PFOV's and the lens mapping. Since the crosshatch is defined on a plane, the PFOV's cannot equal 180 degrees (or a 90 degree half-angle) when using a tangent lens . Even approaching 180 degrees PFOV may cause problems with the tangent mapping. The reason is that the tangent of 90 degrees is infinity, and the definition of an infinite plane is not possible. Other lens mappings may allow more than 180 degrees PFOV, but this must be verified by the user for those mappings.

2.3 The Projection Lens

The projection system model allows the selection of two basic lens mappings via the input file. These selections are either the distortion-less tangent θ mapping, or a theta mapping. Other lens mappings may be used by modifying the NVDPMAP source code where the size of the crosshatch is calculated and where the projection onto the FFP is performed.

This following section discusses the projection lens model used by the NVDPMAP dome display analysis programs. Included is a derivation of the general projection lens mapping equation from object space to image space, and a lens model diagram.

2.3.1 Projection Lens Theory - For the purposes of the Visual Display Parameters project projection lenses are modeled as having the object located at the back focal plane of the lens and the image projected toward an infinite conjugate plane. These locations fall out of the lens equation $1/F = 1/o + 1/i$, where the object distance, o, is equal to the focal length, F (measured from the principal plane), and therefore the image distance, i, is infinity.

In the lens model, the projected image is considered to be at infinity. This assumption in the lens model is based on the fact that an image distance greater than 10 times the focal length, F, will result in an insignificant deviation of the required object position relative to the back focal plane. Since the image distances for the projection systems we are concerned with are usually greater than 100 times F, and the lens is typically focused for infinity, the object and image locations of this lens model can be considered correct for the projection model.

For a lens modeled as projecting a real image to infinity, a relationship exists between the radial distance, r, of an object point from the optic axis and the projection angle, θp, from the optic axis in image space. The distance r is measured on the BFP in object space. This relationship can be expressed generally by an equation of the form:

$$r = F * f(\theta p) \quad , \qquad (2.3\text{-}1)$$

where $f(\theta p)$ is a function describing the relationship between the object point radial distance and the angle of projection for a lens of focal length F.

This general projection lens equation can be derived from a special case of the Lagrange Theorem for a lens system with infinite conjugates, where the object is at the focal plane and the image is at infinity. (2) The Lagrange Theorem defines a constant relationship, called the optical invariant, that gives a relationship between conjugate object/image planes

and their: (1) object and image heights, (2) ray angles from the optic axis, and (3) indices of refraction, n and n', of the optical mediums. For a ray directed through an optical system to satisfy the Lagrange theorem, the products of these three parameters in both image and object space must be equal. The Lagrange invariant is typically applied to lenses that are 'perfect lenses', which have no abberrations and, more importantly, no distortion. Using the optical invariant, the radial image position on the BFP of a 'perfect lens' versus the projection angle is mathematically derrived in reference 2. The result of the above object/image conditions allows the relationship between the object radial position and the ray projection angle to be expressed as:

$$r = F * \tan(\Theta p) \quad . \qquad (2.3\text{-}2)$$

Equation 2.3-2 gives the radial distance from the center of the lens BFP for the intersection of a ray entering a lens with focal length F at an angle of Θp from the optic axis. To find the angle of projection for a specific radial distance use the inverse of 2.3-2, or:

$$\Theta p = \tan^{-1}(r/F) \quad . \qquad (2.3\text{-}3)$$

Since the invariant describes a lens which adds no distortion to an image, equations 2.3-2 and 2.3-3 are the mapping equations for a lens which is considered distortion-less. Equation 2.3-2 can be called a camera mapping, and equation 2.3-3 a projection mapping for a tangent lens.

A more general mapping equation would take the form of equation 2.3-1, where the angular function, $f(\Theta p)$, may no longer have the one-to-one linear relationship between the object and image planes of the tangent map. Two other practical functions for $f(\Theta p)$ are: $f(\Theta p) = \Theta p$(in radians), or $f(\Theta p) = \sin(\Theta p)$. These other functions of Θp are often the mapping functions of lenses used in simulation projection systems where wide angle displays are needed. In actual projection lens systems the lens mapping function may approximate one, or a combination of, the above functions of tangent, sine, or Θp in radians. Deviations from these three functions usually occur and attempts at reducing the deviations is part of the lens design process. When using the above general lens mapping (equation 2.3-1), the lens diagram figure 3.3-1 applies.

In the diagram, the object is located on the back focal plane, o = F, and the image is projected towards infinity. When specifying a projector lens position, the location of the second principle point, P2, should be given. The positions of the projection lens object plane and first principle plane are not needed, since the lens mapping equation specifies their relationship to the projection angle from the second principle point.

(2) Kingslake, R.,"Optical System Design", Academic Press, N.Y., 1983, pp.43-45 .

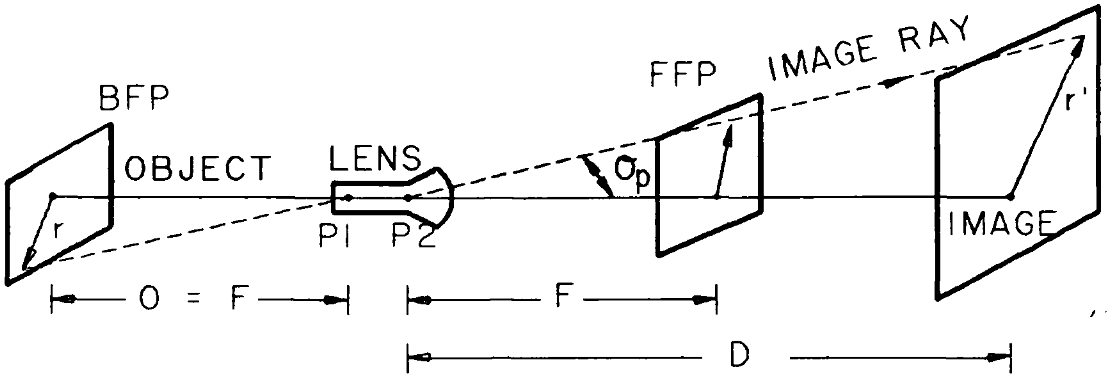


Figure 2.3-1 Lens Model Diagram

2.4 Image Distortion

For visual simulation applications, distortion is the change in the perceived geometry of a projected object compared with the object geometry that would be seen in a real world situation. In a dome projection system, there are often two causes of image distortion. One cause is the lens mapping. The other is the positioning of the viewer and projector, relative to both the dome center and to each other.

2.4.1 Optical Distortion - The first type of distortion is the radial distortion associated with the projection of an image through a lens, and is called optical distortion. This distortion occurs as the image on the back focal plane of the projector is projected through the lens, and may be observed on the front focal plane of figure 2.2-1 or 2.3-1.

Optical distortion is directly related to the lens maping function. If a tangent lens is used, the image will not be distorted by the lens mapping as discussed above. For a tangent lens, the image on the front focal plane will have the same geometry as the image on the target plane (although a right-to left and top-to-bottom reversal of the image occurs). When a lens with another mapping function is used, the image on the front focal plane will show effects of the alternate lens mapping function. In general, a theta mapping function will cause a 'barrel' distortion of a square shape, while a sine mapping will cause a 'pincushion' distortion of the same square shape. The theta mapping is used often when projecting onto the interior of a dome surface, for the screen shape partially reverses the barrel distortion effect, and reduces the amount of distortion correction

required. The sine mapping could be used when back projecting onto the exterior of a dome.

2.4.2 Geometric Distortion - The second type of distortion in a projection system is termed geometric distortion. This distortion involves the projection of imagery onto a screen at angles other than normal to the screen surface. If the screen surface is curved, as in a dome, geometric distortion causes straight lines projected onto the screen to be viewed as curved lines to the viewer. If the screen is flat, then keystoning of the imagery occurs, which can cause rectangles to become trapezoidal. The amount of geometric distortion depends on the shape and radius of the screen, and the separation between the viewer and projector. As the viewer to projector distance is increased, the distortion will also increase, and the apparent size and shape of the objects projected will vary accordingly.

2.4.3 Distortion Output And Calculation - Distortion of the projected crosshatch test pattern is shown visually in the perspective output graphs. The distortion percentages give the amount of video raster distortion from a linear raster. Distortion percentages are labelled about the outer edge of the crosshatch. The distortion calculations in the NVDPMAP program are handled by the subroutine TBLDIST.

The distortion percentages given are calculated according to a definition from the Institute of Radio Engineers (IRE) Standards for Television. (3) This definition was chosen because video is the most common source of imagery for wide-angle dome displays. In the IRE definition the percentage distortion is given relative to the vertical picture height. The net displacement of a image point from its ideal location is called the Geometric Position Error (GPE). The GPE is divided by the picture height and multiplied by 100 to arrive at the percentage distortion. Typically the distortion percentages are given at the corners of the picture, where distortion is at its maximum. In the NVDPMAP output, distortion percentages at the midpoints of the bounding edges of the picture are also given.

2.5 Display Photometry

This section deals with the projection of light in a spherical screen and the amount presented to the viewer. The photometric theory discussed below is incorporated into a subroutine, LUMVAR, called by NVDPMAP, and performs all luminance calculations.

(3)"IRE Standards for Television : Methods of Measurment of Aspect Ratio and Geometric Distortion", Proceedings of the IRE, pp. 1098-1103, July 1954.

2.5.1 Luminance Calculations - As part of the luminance calculations, the illumination on the screen at each crosshatch intersection is found. The luminance available to the viewer is then calculated by taking projection geometry and screen gain into consideration.

NVDPMAP offers two methods of determining screen illuminance. One method starts with the luminance on the projector target plane, and includes the effects of the lens system on the transmission of the projected light. The second method uses the intensity output at the projection lens exit pupil, which already includes the effects of the lens system on the light transmission.

2.5.1.1 Illumination Calculations With Lens Effects - For this analysis, consider an optical system modeled with a lens imaging an element dS of a flat source object onto a flat screen, as in figure 2.5-1.

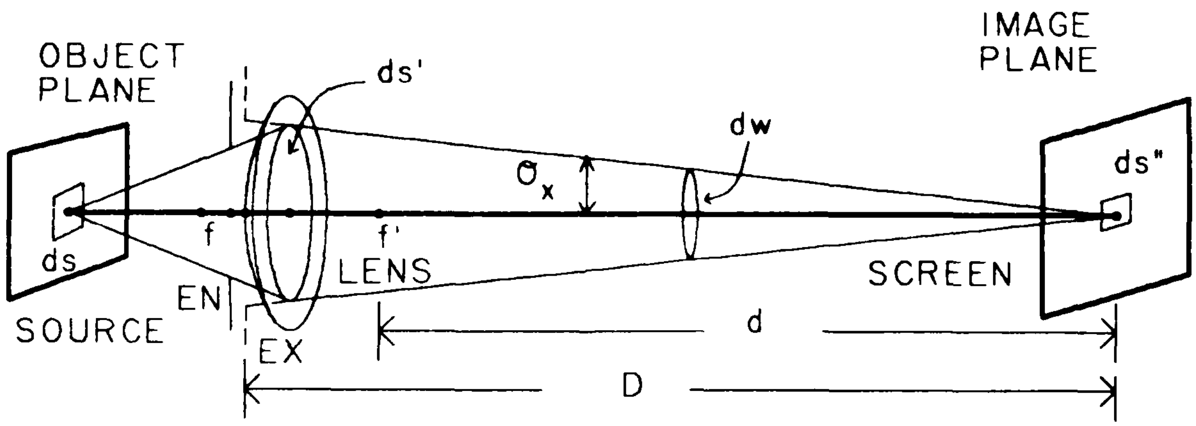


Figure 2.5-1 On-Axis Illumination Model

The source for wide angle displays is usually a video image. The video raster may be considered to have a flat field with a constant luminance, B, across the projection lens object plane. However, the flat field input may not give a constant luminance across the video raster. The luminance may be Bo at the center of the object plane and show a general decrease in luminance with increasing radial distance from the center of the object plane. This object plane luminance may be expressed as :

$$B(r) = Bo * b'(r) \quad , \qquad (2.5\text{-}1)$$

where b'(r) relates the fraction of the Bo center luminance at a radial distance of r from the object plane center . This function is of course dependent on the specific source and in many cases may be neglected due to its small effect , thereby assuming a constant luminance across the object to be projected. (B(r) = B = constant)

The above video source may be considered to be of the Lambertian type, which emits luminous flux according to Lambert's Law, so that $B(\Theta) = Bo$. However, in some cases, the video source may not be lambertian, and its intensity output may be a function of an alternate function of Θ from the source normal rather than the lambertian cosine function. This source brightness variation may be expressed as:

$$B(\Theta) = Bo * b(\Theta) \quad . \qquad (2.5\text{-}2)$$

The combined effect at the source can then be expressed according to the function:

$$B(r,\Theta) = Bo * b'(r) * b(\Theta) \quad , \qquad (2.5\text{-}3)$$

but, again, may be left out of the calculation due to their small effect.

In general, light passing through the glass elements of a lens will experience the combined effects of refraction, reflection, and absorption. Of concern in this analysis is the amount of light from dS that is transmitted through the lens , and directed towards the screen element dS''. Transmission through the lens may be expressed as a constant fraction for the entire projected field, T, or may be expressed as a function of the angle of projection relative to the on-axis transmission of To. The expression can be written as :

$$T(\Theta p) = To * t'(\Theta p) \quad , \qquad (2.5\text{-}4)$$

where $t'(\Theta p)$ is the fraction of light transmitted through the lens at the angle of Θp from the projector axis. In general, the light transmission is reduced as the angle of projection increases. In order to consider the effect of transmission, data for transmission across the range of projection angles must be known and a suitable function determined for $t'(\Theta p)$. For less critical cases the transmission may be considered to be a constant that is equal or less than unity.

The lens exit pupil, dS', accepts the illumination from dS, and passes the light on to the screen element dS'' (less transmission effects). The lens exit pupil, dS', takes on the luminance of the source object , and may be considered as the source illuminating dS''. The illumination on-axis for dS'' from the exit pupil which subtends a solid angle of dw (where dw equals $pi*sin^2(\Theta x)$) to the image is :

$$E = To * Bo * pi * sin^2(\Theta x) \qquad (2.5\text{-}5)$$

in lumens per unit area.(4)

(4) "The Principles of Optics", Hardy and Perrin, p. 411, McGraw Hill Book Co.,Inc., N.Y., 1932.

2.5.1.1.1 Off-Axis Illumination For Flat Screens - To complete the illumination calculations, we must consider the three effects of off axis projection of the flux, which are depicted in figure 2.5-2. Normally, the image is directed onto a flat screen for viewing, and most published analyses of projected illumination are for the flat screen case. The use of a spherical screen alters the traditional calculation of illuminance and complicates the calculations. In order to fully explain the illumination model, the more familiar flat screen case will be explained first, followed by the changes necessary for a spherical screen.

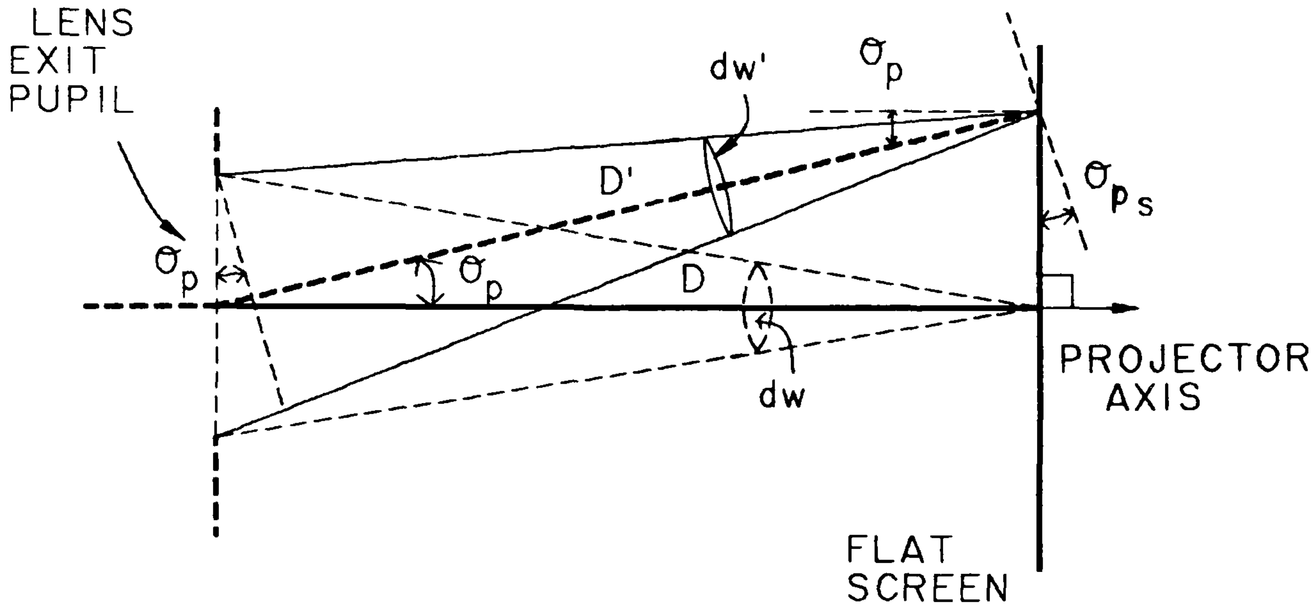


Figure 2.5-2. Off Axis Projection

The first lens effect for off axis projection is the reduction in area of the lens exit pupil as the ray is projected at an angle from the optic axis. If there is a well-defined pupil inside the lens with no vignetting or pupil distortion, the area of the exit pupil is reduced by the cosine of the projection angle, and hence the amount of flux proceeding in that direction is reduced. This exit pupil area change may be expressed as a change in the solid angle, dw, subtended by the pupil to the image point by including the cos(θp) effect on the pupil area for on-axis projection, (or dw' = pi * sin²(θx) * cos(θp)).

The second off axis effect is the increased distance, D', to the flat screen as compared to distance, D, on axis. This effect adds another term because the distance to the source becomes D / cos(θp). Hence the solid angle of the exit pupil is decreased by the cos²(θp) due to the increased

distance.

A third effect for off-axis projection is the increase in the area illuminated on the screen. This is due to the angle of incidence, θps of the flux on the screen relative to the screen normal. Here the area is increased by the inverse of the cosine of θps with a corresponding illumination reduction by $\cos(\theta ps)$. In the case of the flat screen parallel to the source, θps is equal to θp, and the $\cos(\theta p)$ can be substituted.

The total effect on the illumination for rays projected off-axis onto a flat screen due to the above solid angle changes is a $\cos^4(\theta p)$ term, which is the well known cosine 4th law of projected illumination. Adding in the effects of transmission and variation in source flux the illumination projected onto the flat screen can be written as:

$$E = T(\theta p) * B(r,\theta) * \cos^4(\theta p) * pi * \sin^2(\theta x) \quad . \qquad (2.5\text{-}6)$$

Since the angle θx is not readily available, it is desireable to have a means of calculating the solid angle of the exit pupil from data that is easily obtained. Readily available data found on a lens is its focal length, F, and infinite conjugate f/# . The infinite conjugate f/# is the f/# of the lens when the object is at infinity and the image is at the focal plane. The effective f/# of the lens, f/#eff, (for finite conjugates where neither the object or image is at infinity) is equal to f/# * (1 + d/F) on the image side of the lens. Here d is the distance to the image from the second focal point of the lens (figure 2.5-1). Using the relation , f/# = 1 / 2 * NA , where NA is the numerical aperture of the lens and is equal to $\sin(\theta x)$, equation 2.5-6 can be rewritten as :

$$E = \frac{T(\theta p) * B(r,\theta) * \cos^4(\theta p) * pi}{(2 * f/\#)^2 * (1 + d/F)^2} \quad , \qquad (2.5\text{-}7)$$

or,

$$E = \frac{T(\theta p) * B(r,\theta) * \cos^4(\theta p) * pi}{(2 * f/\#/F)^2 * (F + d)^2} \quad . \qquad (2.5\text{-}8)$$

in order to facilitate later computations.

2.5.1.1.2 Off-Axis Illumination For Spherical Screens - This section discusses the changes in the above illumination equations that occur when projecting onto a spherical screen.

The spherical projection model in NVDPMAP involves the projection of a flat field video image through a projector exit pupil located at a position P(xp,yp,zp) onto a dome screen as in figure 2.2-1. The optical axis of the projector is directed towards a point on the screen identified as PCTR(xpctr,ypctr,zpctr), which results in an amount of illumination incident on the screen about PCTR. The image illumination is found by

dividing the object into N elements, centered about each crosshatch intersection, and then following their projection onto the screen.

Principle rays leave each elementary area of the object at angles of $\Theta(N)$ from the object normal, **Nob**, enter the lens and then leave the exit pupil at angles of $\Theta ex(N)$ from the exit pupil normal, **Nex**. The angle Θ can be considered to be equal to $\tan^{-1}(r/F)$ for this simplified lens system, and Θex is the angle of the exiting principle ray relative to the exit pupil. This exit pupil angle is considered to be the same as the angle from the optic axis, Θp, as determined from the lens mapping equation 2.3-1. The rays are incident to the screen at angles of $\Theta ps(N)$ from the normal to the screen surface, **Nscr**. For a dome screen, this normal is the dome radius vector. The intersection point on the screen for each of the rays is identified as PT(xpt,ypt,zpt), and the distance from the exit pupil to each of the PT(N) points is labelled as D(N).

The effect of the off-axis projection is a reduction of the illuminance, however for the case of the spherical screen, the cosine 4th law does not apply. Therefore equation (2.5-7) must be rewritten to take into account the changes occuring from the projection onto a spherical screen.

When projecting onto a spherical screen, the effects of transmission and source flux variation are written in the same manner as eq. (2.5-7), but the $\cos^4(\Theta p)$ term is broken down into three separate terms. First is the change in the exit pupil area term for off-axis projection. The $\cos(\Theta p)$ term will still hold, unless the lens has been designed to increase the area of the exit pupil when projecting off-axis. In the general case the area change may be expressed as $h(\Theta ex)$, which is considered to be equal to $\cos(\Theta p)$ for a typical lens. The second and third changes to equation (2.5-7)'s $\cos^4(\Theta p)$ term occur because the Θp and Θps angles are not opposite interior angles, and because the distance to the screen is not a function of $\cos(\Theta p)$. In order to properly account for the distance changes, the actual distance , d', to each imaged area must be used instead of the $\cos^2(\Theta p)$ term used to modify the on-axis solid angle. For the increased area effect due to the oblique projection onto the screen surface, the actual angle from the screen normal, Θps, must be used in the cosine term. Incorporating these changes, the off axis illumination projected onto a spherical screen is written as:

$$Esph = \frac{T(\Theta p) * B(r,\Theta) * pi * h(\Theta p) * \cos(\Theta ps)}{(2 * f/\# / F)^2 * (F + d')^2} . \qquad (2.5\text{-}9)$$

Figure 2.5-3 depicts the off-axis projection angles and distances for equation 2.5-9 .

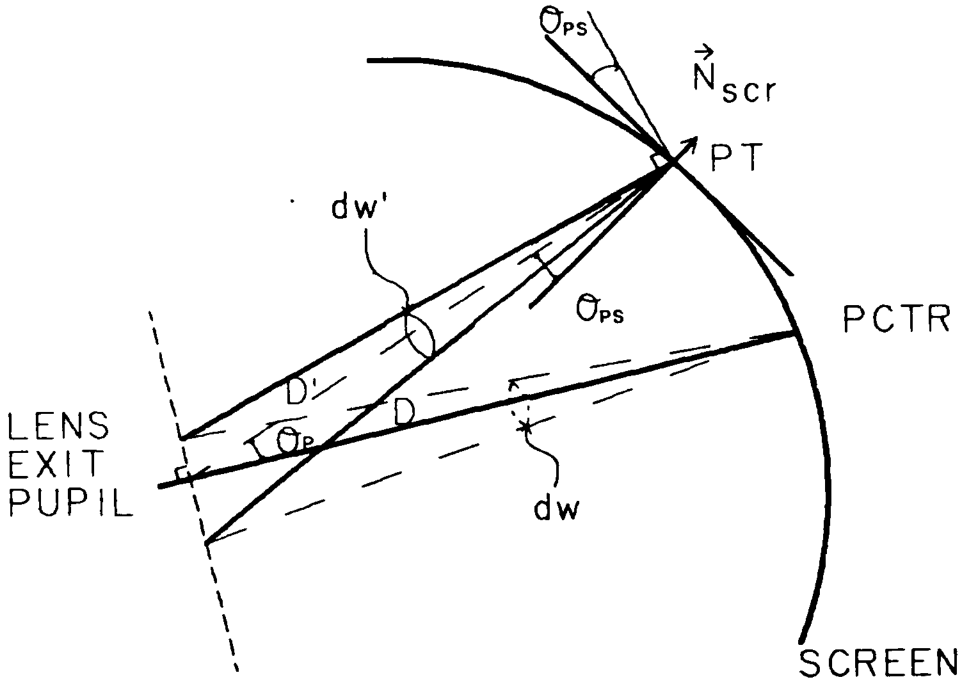


Figure 2.5-3. Spherical Screen Off-Axis Projection

From figure 2.5-1, the distance D is an approximation of the (F + d') distance, since D is measured from the exit pupil and not the second focal point. Substituting D for (F + d'), the illumination equation can then be written as:

$$Esph(N) = \frac{pi * T(\theta p(N)) * B(r(N),\theta(N)) * h(\theta p(N)) * \cos(\theta ps(N))}{(2 * f/\# / F)^2 * D(N)^2} \quad (2.5-10)$$

for each of the N elements of the image.

2.5.1.2 Illumination From Projector Intensity Output - Equation 2.5-10, while describing the majority of the illumination effects in theory, may not be a suitable equation for all illumination calculations. For example, when using a light valve for the image projector, a reading of the target plane image luminance is difficult to obtain. Often, the functions t(θex), b'(r), and h(θex) are not readily available, and their effects may not be easily separated from each other.

Other methods of collecting the data could make the analysis task easier. The function b(θ) could be considered to be a constant equal to unity. Available manufacturer's data, such as total lumens output, may be

useful in finding the input luminance, if we neglect the variations due to the functions t, b', and h. However, the result is a poor description of the projector output, since variations due to the projection angle, Θp, are not considered. Alternately, the measured projector intensity output (in lumens per steradian) can be used for the screen illuminance calculations. Use of the measured light output of the projector would include the above variations, but they would not be independently measured.

Two options exist for finding the intensity output of the projector. First, the intensity can be assumed to be constant with Θp. Using a constant intensity would be consistant with a relative luminance analysis. This intensity could be provided through the manufacturer's total lumens output value divided by the solid angle of the projected field. The solid angle can be found by dividing the area of the screen surface illuminated by the square of the distance to the screen.

The second option is to measure the output intensity variations versus projection angle and to derive an actual function, i(Θp), which gives the variation from the on-axis intensity (i.e. I(Θp) = Io * i(Θp)). The approach for these measurements is to record the illumination values versus projection angle. If these values are taken at a constant distance, CD, from the projector exit pupil, then the intensity of the output can be found by multiplying the illumination values by the square of CD. If CD equals one foot, and the illuminantion values are recorded in foot candles, then the illumination values are numerically equal to the intensity values.

To use the intensity variations in the illuminance equation, 2.5-10, consider the following changes. The rearangement of pi / $(2*f/\#/F)^2$ in the equation can be shown to yeild the area of the exit pupil (pi * Rex^2). When the luminance value, B, in lumens per unit area per unit steradian , is multiplied by the exit pupil area, the result is the intensity of the light (or lumens per unit steradian) emitted from the exit pupil. I(Θp) includes the combined effects of t(Θp), h(Θp), and b'(r) on the luminance provided from the target plane. Since we are now considering the net intensity distribution output, which incorporates the functions describing the lens effects, the resulting illumination equation used for this case may be written as:

$$Esph(N) = \frac{I(\Theta p) * \cos(\Theta ps)}{D(N)^2} \quad . \qquad (2.5\text{-}11)$$

Note that the exit pupil of a lens system can take on the luminance of the object when viewed from an image point. For this case the exit pupil of the projection system is considered to have the same luminance as the object (minus transmission losses). In the illumination calculations from measured intensity outputs, the exit pupil is considered to be the source of the luminous intensity, the distance D to an image point is measured from the exit pupil, and the angle Θp is measured from the optical axis. The screen intersection angle, Θps, is calculated for each ray intersection with the screen surface.

2.5.2 Spherical Screen Luminance - The illumination calculations above have taken into account all distances and angles involved in finding the amount of light flux that falls over a unit area of the screen surface. To find the luminance presented to a viewer, we need to consider the effects of the screen material in relation to the incident light and the viewer position. The overall effect at the screen surface is the re-radiation of the incident illumination according to the properties of the screen material. The illumination on the screen from the projection system may now be considered as a new source of light as the incident flux is re-radiated into space.

The re-radiation of the incident light is described in terms of a gain profile, G(θg), defined by the actual luminance radiated at angle θg from the surface normal relative to the luminance radiated by a lambertian surface at the same angle. Using a symmetric polar gain profile :

$$G(\theta g) = Gmax * g(\theta g) \quad . \qquad (2.5\text{-}12)$$

The amount of light radiated along the maximum gain angle is termed the Gmax of the screen. The function g(θg) gives the change in Gmax versus gain angle as compared to a lambertian surface. This function is defined by g(θg) = g'(θg) / cos(θg), where g'(θg) is the screen intensity profile and cos(θg) is the intensity profile of a lambertian surface. As the gain angle increases, g(θg) reduces the gain value. If cos(θg) is substituted for the g'(θg) function, (the case for a lambertian surface) then g(θg) equals unity, and G(θg) = Gmax = 1. Then the gain and luminance is constant for viewing a lambertian surface at angles up to 90 degrees.

Specifying the gain relative to a lambertian surface allows a comparison with a known surface effect. As mentioned above, a lambertian surface has a constant luminance over the range of θg. This constant luminance is due to the radiated intensity from a lambertian suface at θg being a function of cos(θg). Since the elementary surface area presented to a viewer at θg also reduces according to cos(θg), the ratio of intensity (lumens / steradian) divided by the surface area (which yeilds luminance) remains constant for a lambertian surface.

The gain definition allows the distribution of the luminance on the spherical screen to be described as :

$$Bs(N) = G(\theta g(N)) * Esph(N) \quad , \qquad (2.5\text{-}13)$$

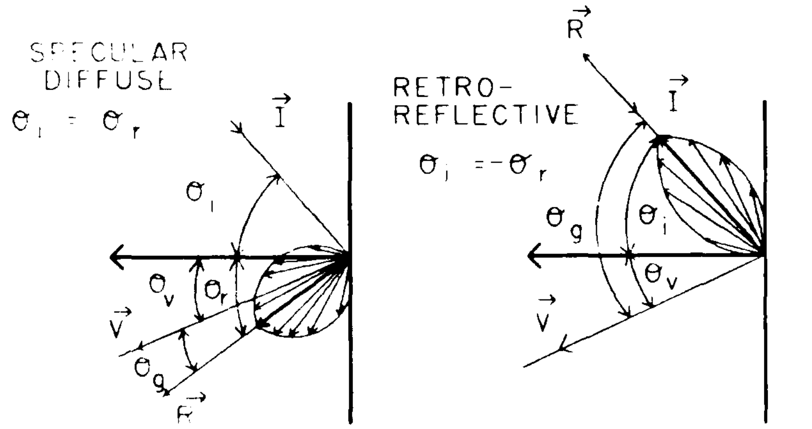
where N is the elementary area index. For a lambertian surface, Gmax is equal to unity, G(θg) is also unity, and the luminance in foot-lamberts is numerically equal to the illumination on the surface.

The maximum gain direction may be described in one of three different ways depending on whether the screen material is retro-reflective (e.g. beaded screen), specularly diffusing, or fully diffusing.

For the retro-reflective case the maximum gain angle is back along the incident ray direction. There usually is a sharp fall-off in intensity beyond a few degrees from the incident ray direction. The retro-reflective gain angle is the included angle found between the incident light and viewing vector. The dot product of these two vectors is used to find the gain angle. A specularly diffusing screen's maximum gain angle is along the reflection angle relative to the angle of incidence, similar to the case of reflection for a mirror. The gain angle is the difference between the reflection and viewing vector. The magnitude of the gain angle is calculated by finding the included angle between the incident light and the viewing vector, θiv, and then subtracting θiv from twice the incident angle. Taking the absolute value of this difference gives the gain angle for the specular-diffuse screen.

The fully diffusing screen (which is a lambertian surface) re-radiates the incident illumination according to Lambert's Law and has a constant luminance at all angles of view. Therefore, a lambertian screen has no preferred maximum gain angle.

Figure 2.5-4 represents ideal gain profiles for a specularly diffusing screen surface, and for a typical retro-reflective screen surface. The maximum gain angle for these two cases is shown along with the θg gain angle calculation for each surface type. In practice the gain profiles may not be symmetrical and may exhibit other selective gain directions. Use of the proper gain angle and gain profile equation allows the calculation of luminance for oblique illumination and viewing of the screen surface.



Specular diffuse	Retro-reflective
$\theta_{iv} = \theta_i + \theta_v$	$\theta_{iv} = \theta_i + \theta_v$
$\theta_g = \lvert 2\theta_i - \theta_{iv} \rvert$	$\theta_g = \cos^{-1}\left(\frac{\vec{R}\cdot\vec{V}}{\lvert\vec{R}\rvert\lvert\vec{V}\rvert}\right)$
$\theta_g = \lvert 2\theta_i - (\theta_i + \theta_v) \rvert$	$\theta_g = \cos^{-1}\left(\frac{\vec{R}\cdot\vec{V}}{\lvert\vec{R}\rvert\lvert\vec{V}\rvert}\right)$

Figure 2.5-4. Ideal Gain Profiles

2.5.3 Luminance Output - Luminance is defined as an amount of lumens radiated from a surface area into a unit steradian cone. The visual perception of luminance is often termed brightness. In these programs luminance values are given in Foot Lamberts, which have units of Lumens / sq.foot / steradian.

The luminance output from the NVDPMAP program is given in the form of contours drawn on top of the perspective and aitoff maps. Luminance values are found at each of the crosshatch intersections and used in the contouring process to show percentage luminance variations across the imagery. A maximum variation of 50% across an entire display area is suggested as a perception limit, with a 10% variation limit between adjacent view window boundries. (5)

Contour levels are set in percentage decrements from the peak window luminance on each perspective map . On the aitoff maps, the peak luminance of all windows in the projection system is used as the peak reference. The percentage levels used are 5, 25, 50, and 75% down from the peak luminance. The 5% increment was chosen to highlight the peak luminance area. The 25% increments were chosen to show the location of the visually perceptable luminance drop-off at 50%.

Additional luminance output given is the minimum and maximum luminance values of each view window. These values (in FtL.) are placed in the upper right corner of the perspective maps, and in the lower right corner of the aitoff maps.

2.6 Display Resolution

This section discusses the pixel resolution calculations in the display analysis program. The resolution calculations are performed by the subroutine PIXRES.

2.6.1 Resolution Calculations - The resolution section of the NVDPMAP program maps pixels about each of the crosshatch test pattern intersections on the input object. The pixels are sized according to the aspect ratio of the pattern and the number of lines and pixels on the input video image. These pixels are projected onto the dome display screen to be "viewed", and the angular subtense of the pixels to the viewer is calculated.

(5). "Design Handbook for Imagery Interpretation Equipment", Richard J. Farrell, John M. Booth, p.3.2-48, Boeing Aerospace Co., Seattle, Washington, Feb. 1984.

The following figure shows the arrangement of a pixel about an intersection of the crosshatch pattern. In the figure the "*" symbol represents a crosshatch intersection point, and the "#" symbol represents a pixel corner point.

```
                                           *-------*-------*-------*-------*~~
  (X1,Y1)       (X2,Y2)                    |       |       |       |       |
    #1<---------> #2                       |   #1-|--#2    |       |       |
  P ^   PWIDTH    |                        |   |   |  |    |       |       |
  H |             |                        *---|--*--|----*-------*-------*~~
  E |  (XCROSS,   |                        |   |   |  |    |       |       |
  I |     *       |       ----->>>         |   #4-|--#3    |       |       |
  G |   YCROSS)   |                        |       |       |       |       |
  H |             |                        *-------*-------*-------*-------*~~
  T v             |                        |       |       |       |       |
    #4----------- #3                       |       |       |       |       |
  (X4,Y4)       (X3,Y3)                    |       |       |       |       |
                                           *-------*-------*-------*-------*~~

        PIXEL                                        CROSSHATCH
       DIAGRAM                                        PATTERN
```

Figure 2.6-1. Crosshatch Resolution Pixels

Lines drawn between the four corner points form the edge of each pixel. The pixels are centered about every crosshatch intersection, with intersection coordinates represented by (XCROSS, YCROSS).

The equations in table 2.6-1 are used in finding the pixel corner coordinates about each of the crosshatch intersections. In the equations, (HEIGHT, WIDTH) define the size of the projector image to be projected, and (PHEIGHT, PWIDTH) define the pixel size. The pixel size on the object plane, horizontally and vertically, is calculated by dividing the number of lines and pixels in the projected image, "LINES" and "PIXELS", into the above dimensions of the projector image. In the calculation of each pixel's size, "KELLP" and "KELLL" are used as scale factors for PHEIGHT and PWIDTH to provide spacing between pixels.

The coordinates of the four corners of the pixel are found by using the half height and half width of the pixel, (HHEIGHT, HWIDTH), as (X,Y) offsets from the crosshatch intersection coordinates. The variables (TXCOMP(N,PN) ,TYCOMP(N,PN)) identify the Nth crosshatch intersection point of the pattern projected in image window #PN. The four corner coordinates are stored in variables (X1,Y1) to (X4,Y4).

```
PHEIGHT = HEIGHT(PN) / LINES  * KELLL
PWIDTH  = WIDTH(PN)  / PIXELS * KELLP

HHEIGHT = PHEIGHT / 2.0
HWIDTH  = PWIDTH  / 2.0

XCROSS = TXCOMP(N,PN)
YCROSS = TYCOMP(N,PN)

X1 = XCROSS + HWIDTH
Y1 = YCROSS + HHEIGHT

X2 = XCROSS - HWIDTH
Y2 = Y1

X3 = X2
Y3 = YCROSS - HHEIGHT

X4 = X1
Y4 = Y3
```

Table 2.6-1. Pixel Boundry Calculations

After calculation of the pixel corner points, they are projected onto a dome screen and their 3-D screen intercept coordinates are found. The method of projection is identical to the crosshatch projection. These screen pixel coordinates are used with the viewpoint coordinates to define vectors from the viewpoint to each pixel corner point on the screen.

Dot products between these vectors are taken and used to find the angles subtended by the horizontal edges of the pixel (between corner points #1-#2 and #3-#4) and the vertical edges (between corner points #1-#3 and #2-#4). These angles are then averaged to find the average horizontal pixel size, AHSIZE, and the average vertical pixel size, AVSIZE. These angular pixel sizes are stored in single precision format two dimensional arrays with units of arc minutes. The array indexes point to the crosshatch intersection number and the projector number to link the pixel sizes with the crosshatch. The pixel sizes are finally sent to the contouring routine for addition to the perspective or aitoff maps.

2.6.2 Resolution Output - The resolution output is given in terms of the angular size (in arc minutes) of each pixel, both horizontally and vertically, from the viewpoint. These angular pixel sizes are used to show the pixel resolution variation across the projected image by the use of contouring. Separate graphs are drawn for the horizontal and vertical resolution contour outputs. The contours are drawn on the perspective maps

to show the resolution distribution for each individual projector. On the aitoff map, the resolution contouring shows the variations between the various projector windows.

3.0 VDP ANALYSIS PROGRAMS

Throughout the VDP project, many FORTRAN programs were written to assist in analyzing dome display systems. As discussed above, the main program is the NVDPMAP analysis program, however, other programs were found to be helpful in the tasks preceeding the running of NVDPMAP. To make the analysis process easier, NVDPMAP and several supporting programs were arranged in a menu format. Along with these programs, useful VAX command sequences were put in the menu to assist in running the programs. A brief explanation of each menu item and its use is given below.

To use the VDP menu, a VAX command file MENU.COM is run by the user. This command file is located in the [N731RH.MENU] subdirectory on NAVTRAEQUIPCEN's VAX 1. All programs for the menu are also located in this subdirectory, along with any data files created when running the programs. MENU.COM uses VAX command language to set up and run the VDP analysis programs. A help selection is included in the menu to remind the user of input formats and program constraints.

3.1 VDP Menu

Figure 3.1-1 is the menu for the VDP analysis programs. The notes in the upper right of the figure indicate which menu selections require use of the Textronix graphic terminal or IKONAS graphic system.

VISUAL DISPLAY PARAMETERS MENU

PF1	PF2	PF3	PF4
* "7" TRIG FUNCTION	* "8" AITOFF PLOT	* "9" RASTER SHAPE	"-" SPECIAL MENU
"4" HELP	"5" MEASURE SPHERE	* "6" VERIFY SYSTEM	"," DATA DIR
"1" PROJECT VECTORS	** "2" IK TEST PATTERN	"3" DATA INPUT	ENTER
* "0" DOME DISPLAY ANALYSIS		"." EXIT MENU	

* - REQUIRES USE OF TEXTRONIX

** - REQUIRES USE OF IKONAS

Figure 3.1-1. VDP Keypad Menu

The menu layout is intended to represent the keypad on Digital Equipment Corporation (DEC) VT-100, or compatable, terminals. To select any of the menu items, enter the number or symbol in double quotes (" ") that matches the item. Follow this by striking the ENTER or RETURN key. After item selection, the terminal screen will be cleared and an introductory message will be printed identifying the item selected. Instructions will be given and questions will be asked that require user input that is always followed by striking the ENTER or RETURN key.

The keys PF1 through PF4 are not VDP menu items.

When entering 3-D coordinates or spherical angles, the coordinate and angular conventions of subsection 2.2.1 are assumed.

At any time during menu operations or running of programs, the user can return to the main menu by pressing the "CTRL" and "C" keys simultaneously. All programs will be stopped, any menu selections will be exited, and the main menu, figure 3.1-1, will be redrawn on the terminal screen. If "CTRLC" is used to exit any of the FORTRAN programs, it is possible that data output files may have been created within the program that are not complete. These should be deleted by the user.

3.1.1 Dome Display Analysis Selection - This item runs the NVDPMAP dome display analysis program. To run this program, a projector system description is required.

There are two methods of describing the projection system, either by interactive input into the program during run time, or by entering the description into an input file format (see appendix A). The user is offered the option of creating an input file for this selection (see Data Input Selection - 3 below), but one is not necessary. If an input file is not to be used, then the user is prompted by a series of questions for the projection system description and program output options.

To describe the projection system and obtain output graphics, the user should have read the above section 2.0, particularily subsection 2.2, to understand the projection system model.

3.1.2 Project Vectors Selection - This menu item allows the projection of vectors in 3-D space. There are three choices for projection: PTFANG, PTSPH, and PTCYL. Spherical angle sets are given in degrees for these vector projection routines.

PTFANG is used to find the 3-D terminus of a vector of length D, projected in the direction defined by a spherical angle set ($\Theta V, \Phi H$), from an initial 3-D coordinate (XI,YI,ZI,).

PTSPH is used to find the interception point on a spherical surface of a vector projected at ($\Theta v, \Phi h$) from a point within a sphere of radius R. The initial point of the vector is specified relative to the sphere origin in 3-D coordinates. PTSPH is used to find the projector optical axis intercept with the dome screen, which is required for input to NVDPMAP.

PTCYL is similar to PTSPH, except that it is for a cylindrical screen. The interception point of a vector with the cylinder is found. The cylinder's origin is not a singular point, but is a line axis through the cylinder. The 3-D projection point of the vector is then specified relative to the cylinder line axis, which is oriented along the Z-axis.

3.1.3 IK Test Pattern Selection - The IK test pattern selection will draw a crosshatch or checkerboard on the IKONAS graphic system. The IKONAS must have already been be powered up for this selection to work.

The crosshatch/checkerboard, with the number of vertical and horozontal specified by the user, is drawn in white. This selection was intended to be used for generating test projection patterns, but the linearity of the IKONAS camera station did not allow for accurately drawn patterns.

3.1.4 Data Input Selection - Data input options are given for creating input files for the NVDPMAP and VERIFY programs. In response to this selection, a choice for either of the input formats is made.

After choosing which input file to create, a message indicating the choice is written to the screen and some instructions are given. A master input file is opened for editing, which is specially formatted for each program. These formatted files list the variable names against the left margin, with a description in comment fields to the right. The user then uses standard EDT editing commands to replace the variable names with the data describing the projection system and the options desired. See appendix A for a description of the NVDPMAP input file.

3.1.5 Help Selection - This selection provides on-line help for each of the menu items. A help menu is drawn on the terminal for the user to select a keypad help item. Information on that item is then given on the terminal.

3.1.6 Measure Sphere Selection - SPHERE is another display analysis program that assists in measuring a dome screen. The program can be used to measure the dome radius and to find the center, or origin, of the dome. The sphericity of the dome can also be checked to within a few hundredths of an inch.

The program requires the use of specialized measurement equipment to set up a 3-D coordinate measuring system. Equipment required: two auto-collimating theodolites with stands(capable of measurement in arc-minutes or better), a surveyor's 2.0 meter subtense bar with stand, and a method to provide a stable reference point about the dome surface (eg. a small point of light). The auto collimating theodolites provide a means to boresight the two theodolites to each other, and the subtense bar is used as a length reference during setup.

SPHERE prompts the user for the type of measurement to be made. The options include: theodolite baseline measurement, calculation of the dome radius and center, measurment of dome sphericity, and the location of the projector exit pupil and optical axis orientation. Only the baseline measurement task must be performed when running the program, while the remaining tasks can be skipped over to perform another task. For each step of each measurement process, SPHERE gives instructions and accepts measurement data. The option to reenter the data for each point is given for correction of data entry errors. The program performs some error checking on the initial setup measurements, and also has an option for reducing measurement error by making both forward and reverse sightings to each measurement point.

Three output files are created by SPHERE. The output file SPHERE.DAT includes every step taken in the measurement process, including the initial setup, and their final results. SPHRINPUT.DAT contains every data value input during the program run, even those that were replaced. The results of the sphericity measurement calculations are provided for output in another file named SPHRICITY.DAT.

3.1.7 Verify System Selection - A program named VERIFY was written to assist in verifying the NVDPMAP program. The verification consists of the projection of an actual crosshatch test pattern from a known projector location and projection lens. The crosshatch is projected onto a dome screen of known radius with the projector optical axis aligned with a known point on the screen surface. Using a theodolite located at a viewpoint position, the spherical angles to each crosshatch point are measured and used as input to VERIFY. These angles are then used to draw both perspective and aitoff maps of the crosshatch and view window outline. By inputting the verification projection system description into NVDPMAP, theoretical perspective and aitoff maps can be obtained to compare with the maps drawn from measured data.

3.1.8 Trig Function Selection - The Trig function is used to find a lens mapping function or intensity output function for modifying the NVDPMAP default lens mappings and intensity output functions. The program , named LENSFUNC, is menu oriented and has a built in help section.

The program accepts (X,Θ) data and finds an equation that represents the data using trigonometric functions. The trigonometric functions and their power are selected by the user, and the resulting equation is then evaluated against the input data. The functions that can be selected are tangent(Θ), sine(Θ), cosine(Θ), and Θ. Remember that NVDPMAP assumes that Θ is in radians.

The program requests a filename for storing the input data and the results of the program calculations. The input data is stored in a file with the above filename and a filetype extention of .DAT. The results of the calculations are stored in a file with the above filename with DAT added as a prefix. These files are designed to be read by the LENSFUNC program.

3.1.9 Aitoff Plot Selection - When selected, an aitoff map with ten degree angle increments is drawn on the textronix screen. The aitoff map is used to show the spherical angle orientation of objects within a 4 pi steradian solid angle surrounding the viewpoint. The spherical angles consist of separate vertical and horizontal angles with the conventions described in section 2.2-1. The program, AITOFFPLOT, accepts a set of spherical angles in degrees, and connects their plotted positions with lines on the aitoff map. This item is useful in drawing the outlines of objects in spherical angle terms.

3.1.10 Raster Shape Selection - Picking this item runs a program named MAPTAG. MAPTAG was written to calculate the required raster shape of a video projector for forming a image on a dome screen that has no apparent distortion. The program uses the same projection model as NVDPMAP, but the process is reversed to find the raster shape. This program is documented in reference 1.

3.1.11 Special Menu Selection - The special menu contains several functions: Send - sends a message to another terminal, Who - lists the present VAX system users, Dir - allows directory of files outside of the menu subdirectory, Graphic Switch - directs the graphic output to a data file (FOR010.DAT) rather than to the graphic terminal, and Logical List - lists the VAX logical assignments in effect. Graphs written to a data file may be drawn later by 'copying' the file to the graphic terminal using the command - COPY FOR010.DAT TTA7: (TTA7: is the graphics port identification).

3.1.12 Data Directory Selection - The data files used for input to NVDPMAP and VERIFY are listed on the terminal to help in selecting an input file for the programs. Also listed are files with a '.DAT' extension, which are output files from programs run from the menu. The option to edit or delete the data files is also given. New input files can be made by modifying old input files, or old files can be deleted.

3.1.13 Exit Menu Selection - Selecting this menu item causes an exit from the menu command sequence. To exit the menu, you must return to the main menu and select this exit item.

4.0 TEST SYSTEM SAMPLE ANAYLSIS

4.1 Test Case Description

Table 4.0-1 is a sample input file for a six projector display system, TCASEA.DAT;1. This input file is one of the test cases used to check the operation of the VDPMAP program. The projector/viewer arrangement provides a test case that fills the total solid angle field available to a viewer, and introduces no perspective distortion of the images projected.

```
TEST CASE A1                 ! SYSTEM NAME
TRUE,TRUE,TRUE               ! LOGICALS FOR PERSPECTIVE GRAPHS (MAP,LUM,RES)
2.,1.,0.3,0.                 ! PERSPECTIVE GRAPH SCALING DATA
TRUE,TRUE,TRUE               ! LOGICALS FOR AITOFF GRAPHS      (MAP,LUM,RES)
1.0,1                        ! SCREEN GAIN AND TYPE
1,0.                         ! VIEWPOINT MAPPING (W/TANGENT DISTORTION)
FALSE                        ! LOGICAL FOR COORDINATE TABLE OUTPUT

120.0,1                      ! DOME RADIUS IN INCHES
0.,0.,0.                     ! VIEWPOINT
6                            ! NUMBER OF PROJECTORS

-120.,0.,0.,                 ! CENTER OF PROJECTOR WINDOW #1
11,11,                       ! # OF VERTICAL AND HORIZONTAL CROSSHATCH LINES
70,90,                       ! VERTICAL AND HORIZONTAL FIELDS OF VIEW
380,480                      ! LINES, PIXELS
1.0,1.0                      ! KELL_L, KELL_P
0.,0.,0.,                    ! PROJECTOR #1 LOCATION
1.0,2.0,1,1.                 ! FOCAL LENGTH, F/#, MAPTYPE, T% OF LENS #1
2,1963.5                     ! LCODE, FLUXmax

0.,120.,0.,                  ! CENTER OF PROJECTOR WINDOW #2
11,11,                       ! # OF VERTICAL AND HORIZONTAL CROSSHATCH LINES
70,90,                       ! VERTICAL AND HORIZONTAL FIELDS OF VIEW
380,480                      ! LINES, PIXELS
1.0,1.0                      ! KELL_L, KELL_P
0.,0.,0.,                    ! PROJECTOR #2 LOCATION
1.0,2.0,1,1.                 ! FOCAL LENGTH, F/#, MAPTYPE, T% OF LENS #2
2,1963.5                     ! LCODE, FLUXmax

120.,0.,0.,                  ! CENTER OF PROJECTOR WINDOW #3
11,11,                       ! # OF VERTICAL AND HORIZONTAL CROSSHATCH LINES
70,90,                       ! VERTICAL AND HORIZONTAL FIELDS OF VIEW
380,480                      ! LINES, PIXELS
1.0,1.0                      ! KELL_L, KELL_P
0.,0.,0.,                    ! PROJECTOR #3 LOCATION
1.0,2.0,1,1.                 ! FOCAL LENGTH, F/#, MAPTYPE, T% OF LENS #3
2,1963.5                     ! LCODE, FLUXmax
```

```
0.,-120.,0.,                  ! CENTER OF PROJECTOR WINDOW #4
11,11,                        ! # OF VERTICAL AND HORIZONTAL CROSSHATCH LINES
70,90,                        ! VERTICAL AND HORIZONTAL FIELDS OF VIEW
380,480                       ! LINES, PIXELS
1.0,1.0                       ! KELL_L, KELL_P
0.,0.,0.,                     ! PROJECTOR #4 LOCATION
1.0,2.0,1,1.                  ! FOCAL LENGTH, F/#, MAPTYPE, T% OF LENS #4
2,1963.5                      ! LCODE, FLUXmax

0.,0.,120.,                   ! CENTER OF PROJECTOR WINDOW #5
11,11,                        ! # OF VERTICAL AND HORIZONTAL CROSSHATCH LINES
110,110                       ! VERTICAL AND HORIZONTAL FIELDS OF VIEW
380,480                       ! LINES, PIXELS
1.0,1.0                       ! KELL_L, KELL_P
0.,0.,0.,                     ! PROJECTOR #5 LOCATION
1.0,2.0,1,1.                  ! FOCAL LENGTH, F/#, MAPTYPE, T% OF LENS #5
2,1963.5                      ! LCODE, FLUXmax

0.,0.,-120.,                  ! CENTER OF PROJECTOR WINDOW #6
11,11,                        ! # OF VERTICAL AND HORIZONTAL CROSSHATCH LINES
110,110                       ! VERTICAL AND HORIZONTAL FIELDS OF VIEW
380,480                       ! LINES, PIXELS
1.0,1.0                       ! KELL_L, KELL_P
0.,0.,0.,                     ! PROJECTOR #6 LOCATION
1.0,2.0,1,1.                  ! FOCAL LENGTH, F/#, MAPTYPE, T% OF LENS #6
2,1963.5                      ! LCODE, FLUXmax
```

Table 4.0-1. Test Input File

While each projector in this system has the same on-axis intensity output from its exit pupil, the net lumens output of projectors' 5 and 6 would be larger to compensate for the larger projected FOV. The input data for this test case is discussed next.

4.1.1 Block One Data - TEST CASE A 1 is entered as the name of this system in the first record of block one. All graphic outputs are chosen in this example, by setting the perspective and aitoff logicals to TRUE on records two and four of block one. If no perspective outputs are requested, the default perspective screen scaling values, in record three, should still be in the file to preserve the file format. The viewpoint mapping is entered in record six. The mapping selected is a tangent map, which gives a true perspective of the projected patterns.

The screen gain, GMAX, is 1.0, and the screen type is entered as lambertian (GTYPE = 1).

The option of coordinate table output is rejected in record seven.

4.1.2 Block Two Data - Block two specifies the screen radius to be 120.0 inches and spherical in shape. The rest of block two locates the viewer at the dome screen origin EN(0,0,0), and states that the projection system has six projectors.

4.1.3 Block Three Data - Six occurrences of the block three data follow block two, one for each of the six projectors. In each of the projector descriptions, the projected pattern is an 11V x 11H crosshatch formed on a 380 line by 480 pixel projection plane. Other projector variables that are the same for this projection system are: the lens focal lengths (F = 1.0 inch), f/#'s (FNUM = f/2), lens types (LENSTYPE = 1, or tangent map), lens transmission factors (T = 1.0), kell factors (KELLL = KELLP = 1.0), exit pupil locations (EX = (0,0,0) at dome origin), and exit pupil intensity outputs (LCODE = 2, and FMAX = 1963.5 candelas). The intensity profiles of the projectors are considered to be cosine squared functions of the projection angle (relative to the optical axis) by default in the luminance calculation subroutine, LUMVAR.

4.2 Discussion

The arrangement specified in TCASEA.DAT;1 provides a test case for NVDPMAP. The display defined fills the viewer's total FOV with no distortion of the imagery presented to the viewer. Additionally, in the luminance calculations, the screen intercept and gain angles are always zero because of the spherical symmetry of the projectors, viewpoint, and screen surface. Unfortunately, this arrangement is not practical. The positioning of the viewpoint and six projectors at the same point in space, the dome origin, is not possible. However, this test system is useful as an example for the NVDPMAP anaylsis program.

The six projectors can be arranged in two groups: four projectors with images centered about the horizon, and two projectors with their images centered on the poles of the dome screen. The horizon projectors are all set to project an image which measures 70 degrees vertical by 90 degrees horizontal. The horizon view window centers are located 90 degrees apart on the dome equator, where the X and Y axes of the dome centered coordinate system intersect the dome. The Z coordinate (on vertical axis) is zero for all the horizon PCTR's, and the X and Y coordinates alternate between zero and positive or minus R, the dome radius. The arrangement of the horizon projectors provides view windows that horizontally surround the viewer, at the dome origin, with no gaps between the windows. They provide a total FOV of 360 degrees horizontal by 70 degrees vertical, with the vertical field split evenly about the horizon.

Each of the two pole projectors has an 110 degrees vertical by 110 degrees horizontal image size. The upper projector's PCTR is located at the positive Z axis intersection with the dome, (0,0,120.0) inches, and the

lower projector's PCTR is located at the negative Z axis intersection with the dome, or (0,0,-120.0) inches. The edges of the pole projector windows fall on the top and bottom of the horizon windows, which makes it difficult to distinguish the pole projectors' outline on the aitoff maps.

The combined total FOV of all six projectors in this system fills the entire spherical viewing volume, or a 4pi steradian solid angle from the viewpoint.

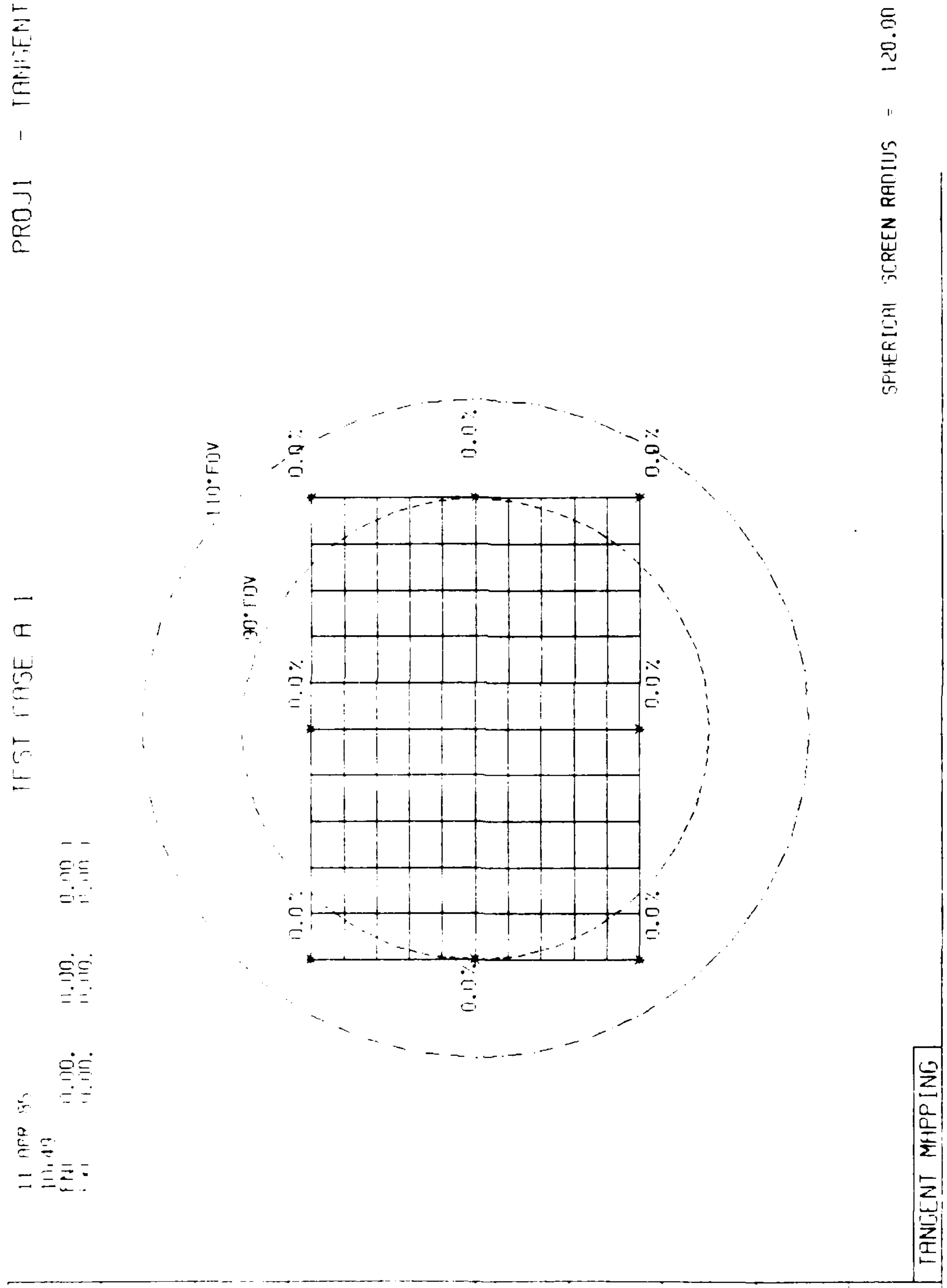
4.3 Test Case Graphic Outputs

Within the two groups of projectors, the horizon projectors and the pole projectors, the same relative geometry exists. Therefore the outputs of only two of the projector perspectives need to be examined to interpret this test case. All perspective maps for the four horizon windows show the same results, while the two pole perspective maps are also identical. In the examination of the perspective maps below, the perspective outputs for projector 1 and 5 are representative of the outputs for the horizon projectors and the two pole projectors, respectively.

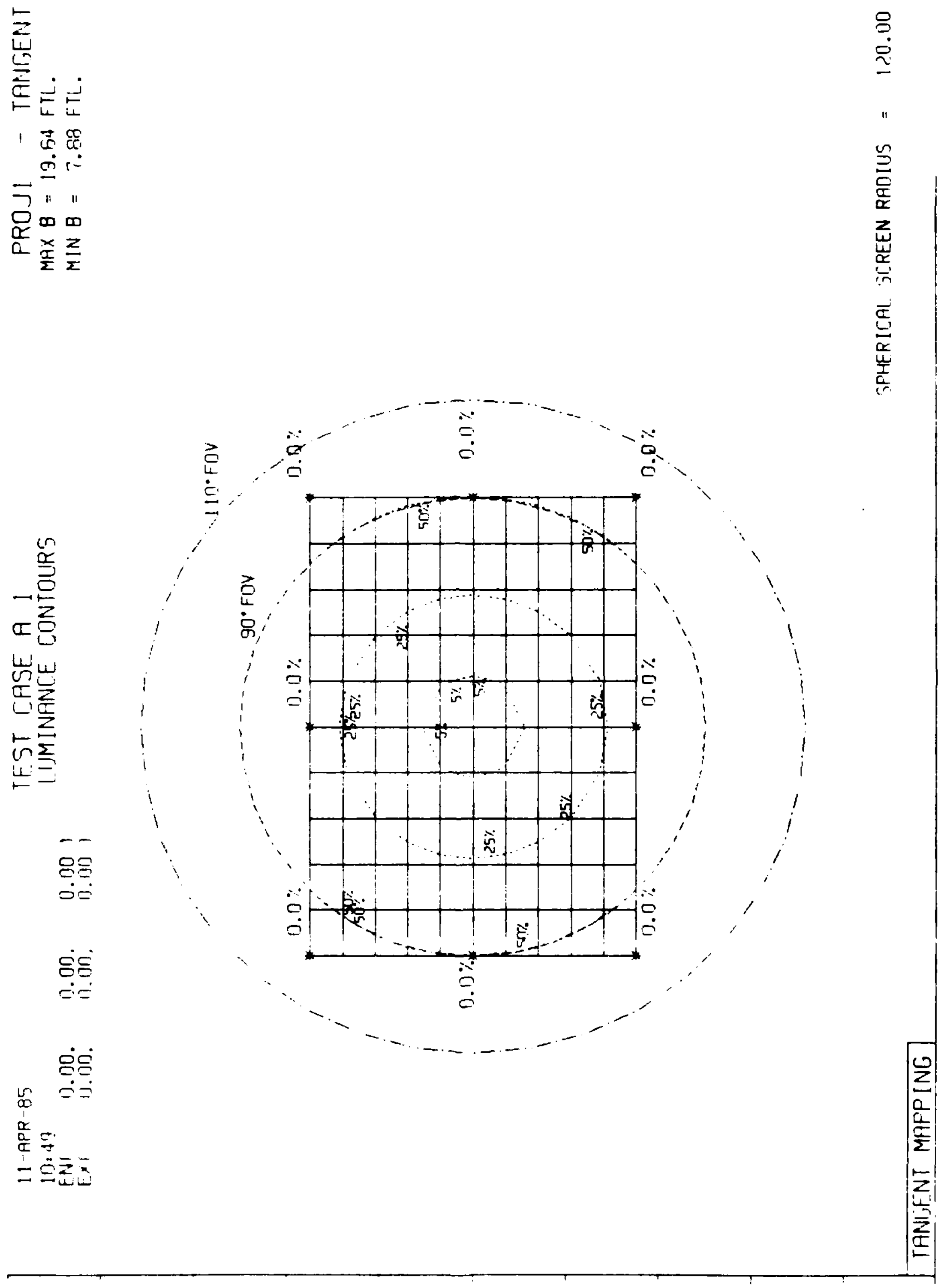
4.3.1 The Horizon Projector Perspective Maps - The perspective maps for all the horizon projectors show the same distortion as figure 4.3-1. Zero distortion percentages are labelled around the perimeter of the crosshatch. Since the projector and viewpoint are at the same location, no distortion of the crosshatch is perceived at the viewpoint. This arrangement shows that the shape of the screen causes no distortion of projected imagery if the viewpoint and projector are coincident.

Information shown on the perspective maps give: the name of the projector system, the date and time, the (X,Y,Z) location of the projector, EX, and viewpoint, EN, the number of the projector and type of lens mapping, and the radius of the screen. The tangent mapping label in the lower left corner indicates that drawing is a true perspective mapping from the viewpoint. Also shown on the figure are FOV circles for showing the 90 and 110 degree FOV's from the viewpoint. These circles are useful in estimating the FOV provided at the viewpoint. Since the projected FOV for the horizon windows are 70 degrees vertical by 90 degrees horizontal, the midpoints of the left and right edges of the crosshatch intersect the 90 degree FOV circle.

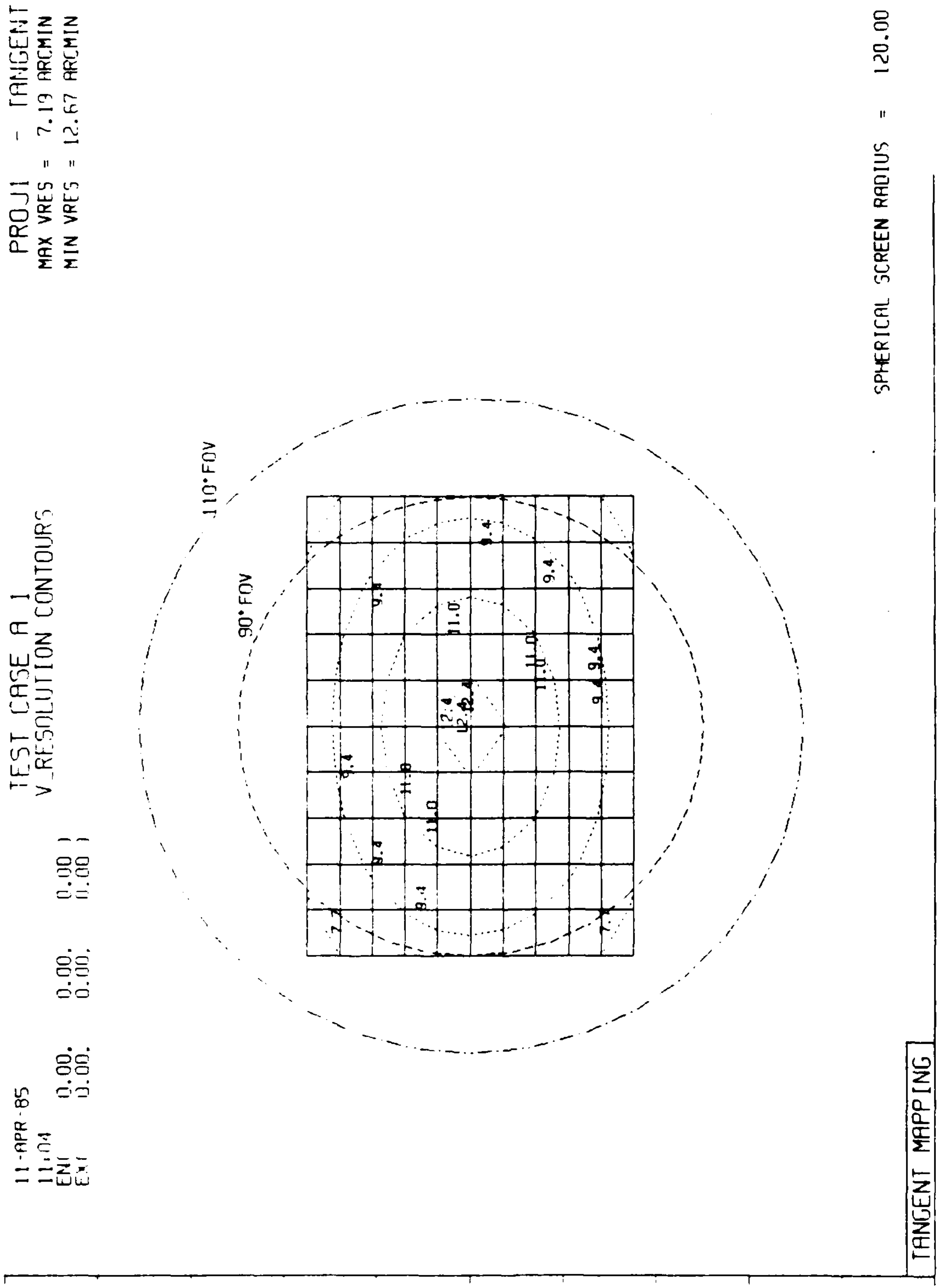
Figure 4.3-2 combines the above distortion percentages with the luminance contour outputs representative of all the horizon projectors. The luminance contours show the peak luminance area in the center of the view window, with a gradual falloff to less than 50% of the peak luminance at the corners of the view windows. In this figure, the 50% contour falls on top of the 90 degree FOV circle and is difficult to see, however the 50% contour labels indicate the contour presence. The maximum and minimum



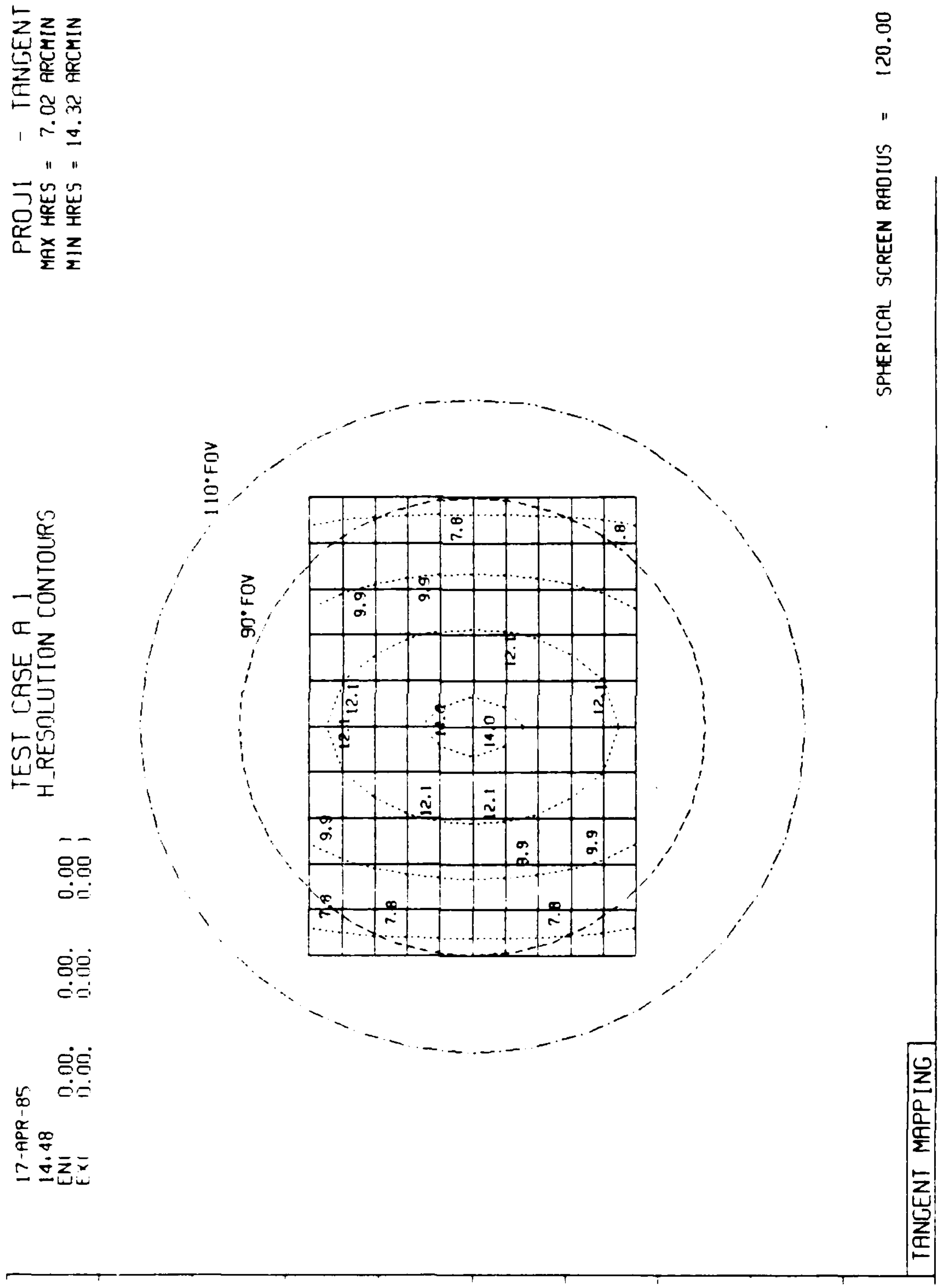
4.3-1. Horizon Projectors Distortion Map



4.3-2. Horizon Luminance Map



4.3-3a. Horizon Vertical Resolution Map



4.3-3b. Horizon Horizontal Resolution Map

luminance values for the view window are found on the upper right corner of the perspective maps, and are listed as 19.64 FtL. maximum and 7.88 FtL. minimum. The maximum luminance can be expected to be found at the center of the 5% contour, and the minimum luminance would be found in the corners of the crosshatch.

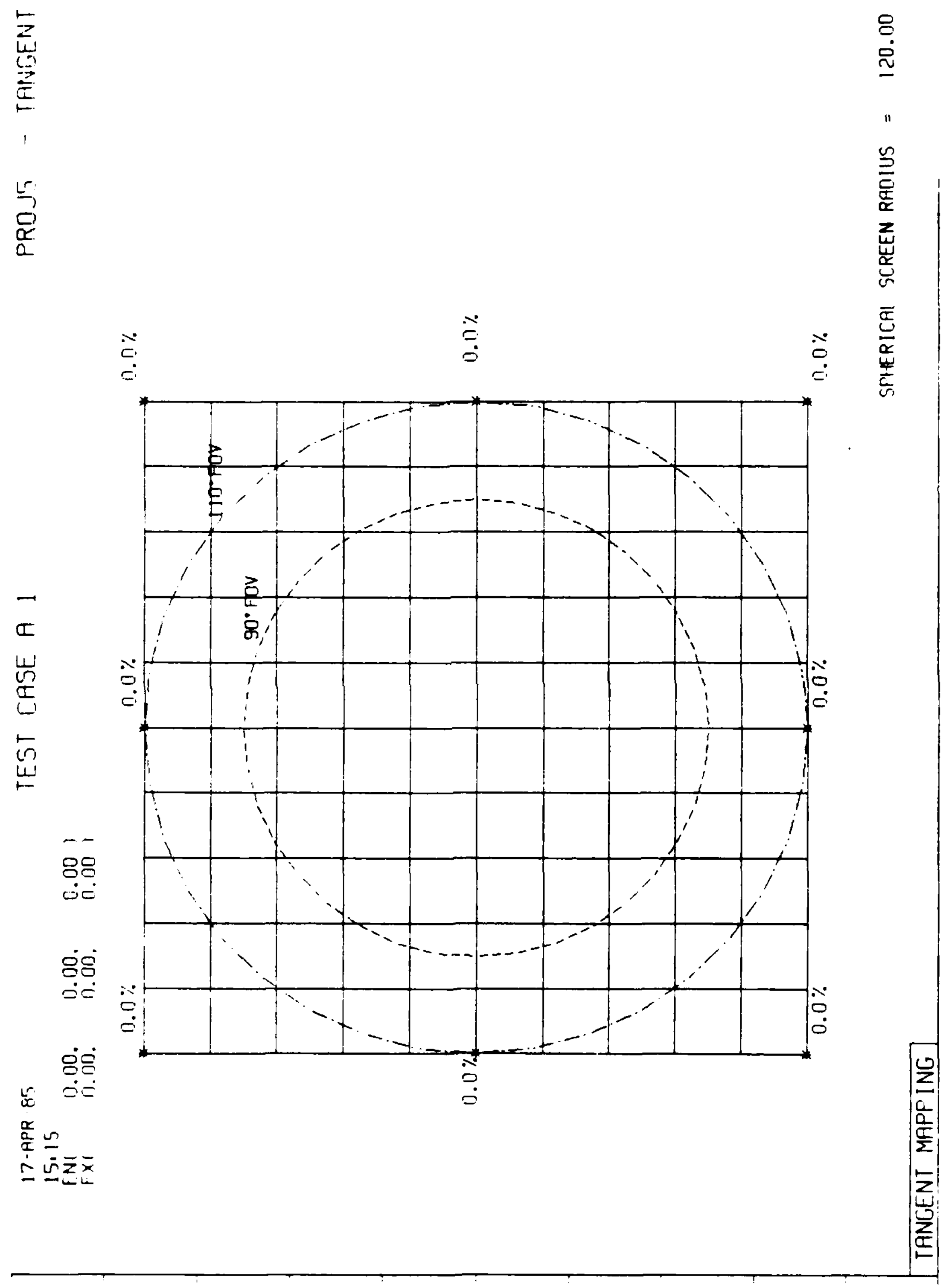
Figure 4.3-3a is one of the resolution perspective maps for the horizon projectors. This figure shows the vertical pixel sizing in arc minutes representative of the horizon windows. On this map, the maximum vertical resolution (smallest pixel) is found in the corners of the view window, while the minimum vertical resolution (largest pixel) is found in the center of the view window. The maximum and minimum vertical resolution values are written in the upper right corner on the resolution perspective map. The maximum vertical resolution is 7.19 arc minutes, and the minimum vertical resolution is 12.67 arc minutes.

Figure 4.3-3b is the second resolution perspective map showing the horizontal pixel resolutions for the horizon windows. The maximum horizontal resolution (smallest pixel) is given as 7.02 arc minutes and the minimum horizontal resolution (largest pixel) is 14.32 arc minutes.

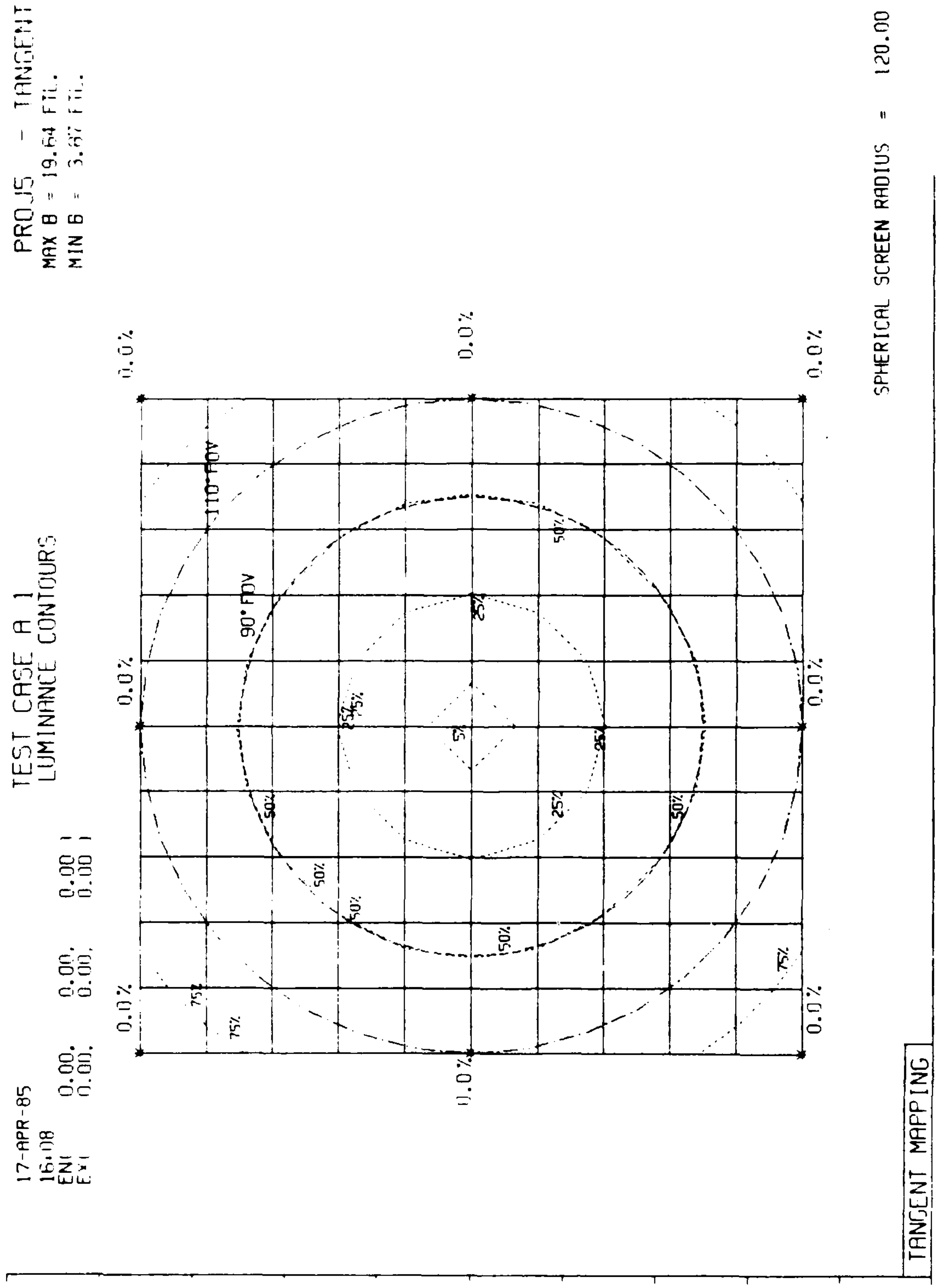
4.3.2 The Pole Projector Perspective Maps - Figure 4.3-4 is a perspective map which shows the distortion on the pole projector view windows. The pole projectors also have tangent type lens mappings and show zero distortion percentages due to the viewpoint and projector coincidence. The projected FOV for the pole projectors is 110 degrees horizontal by 110 degrees vertical. These same FOV's are provided to the viewpoint as indicated by the intersection of the midpoints of all four edges of the view window with the 110 FOV circle.

Figure 4.3-5 is the luminance contouring output for the pole windows. The peak luminance on this map is also located at the view window center, with a drop in luminance toward the corners of the window. Since the on-axis intensity output for the pole projectors is the same as the horizon projectors, the maximum luminance on the pole windows is the same as the horizon windows at 19.64 FtL.. However, since the maximum projection angle for the pole projectors is greater than the horizon projectors, the minimum luminance on the pole windows is less than the horizon windows (3.87 FtL. on the pole windows vs. 7.88 FtL. on the horizon windows). Again, the lower luminance is due to the increased projection angle to the edges of the larger pole windows.

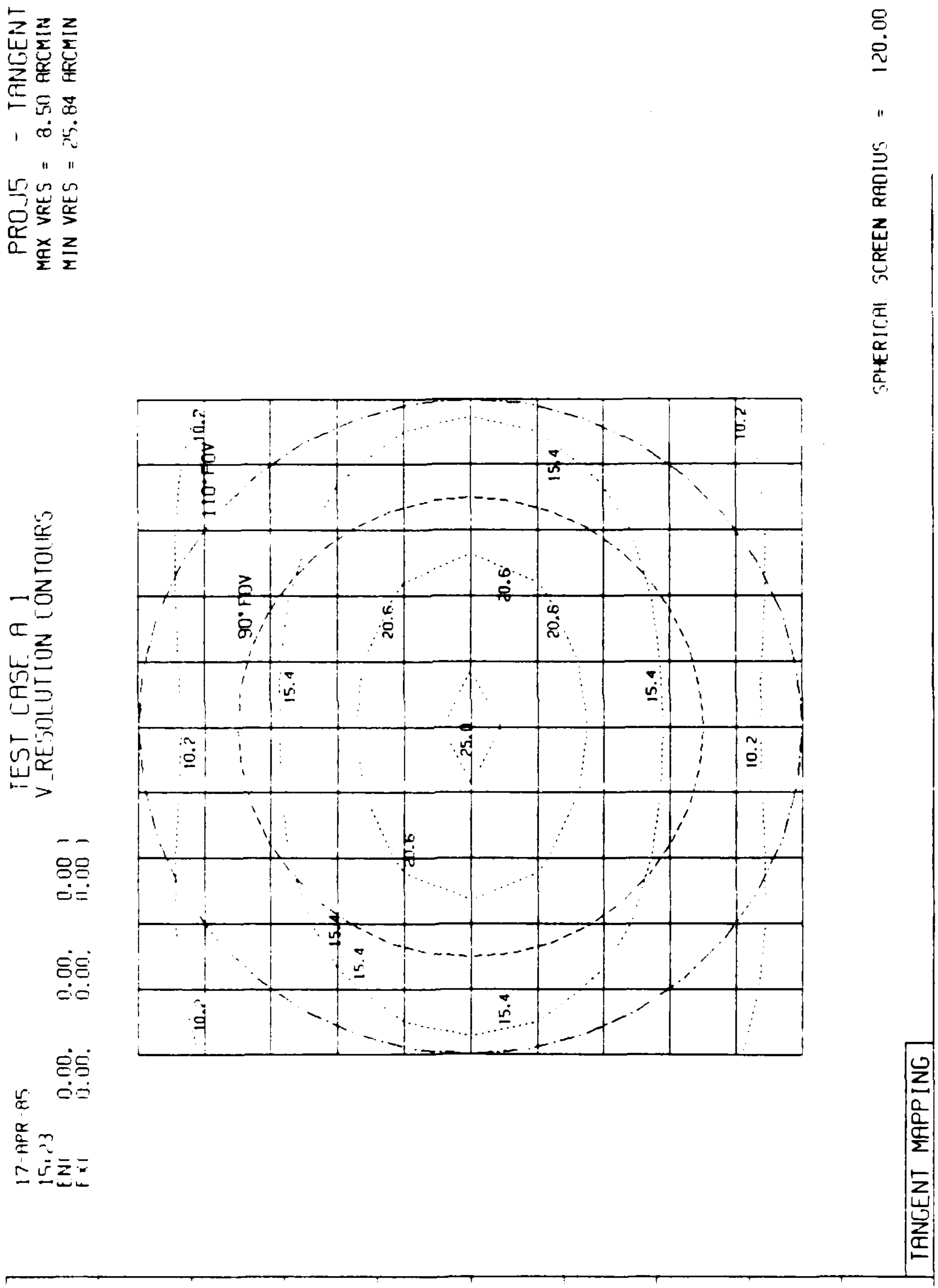
The above luminance values for both the horizon and pole view windows can be quickly verified by considering the input parameters for the projectors. The projectors are located at the center of the dome giving a constant projection distance to the screen of 10 feet and fixing the screen intercept and gain angles to zero degrees in the luminance calculations (eqs. 2.5-11 and 2.5-13). The projector intensity outputs are 1963.5 candelas, and the intensity profiles are cosine squared functions of the



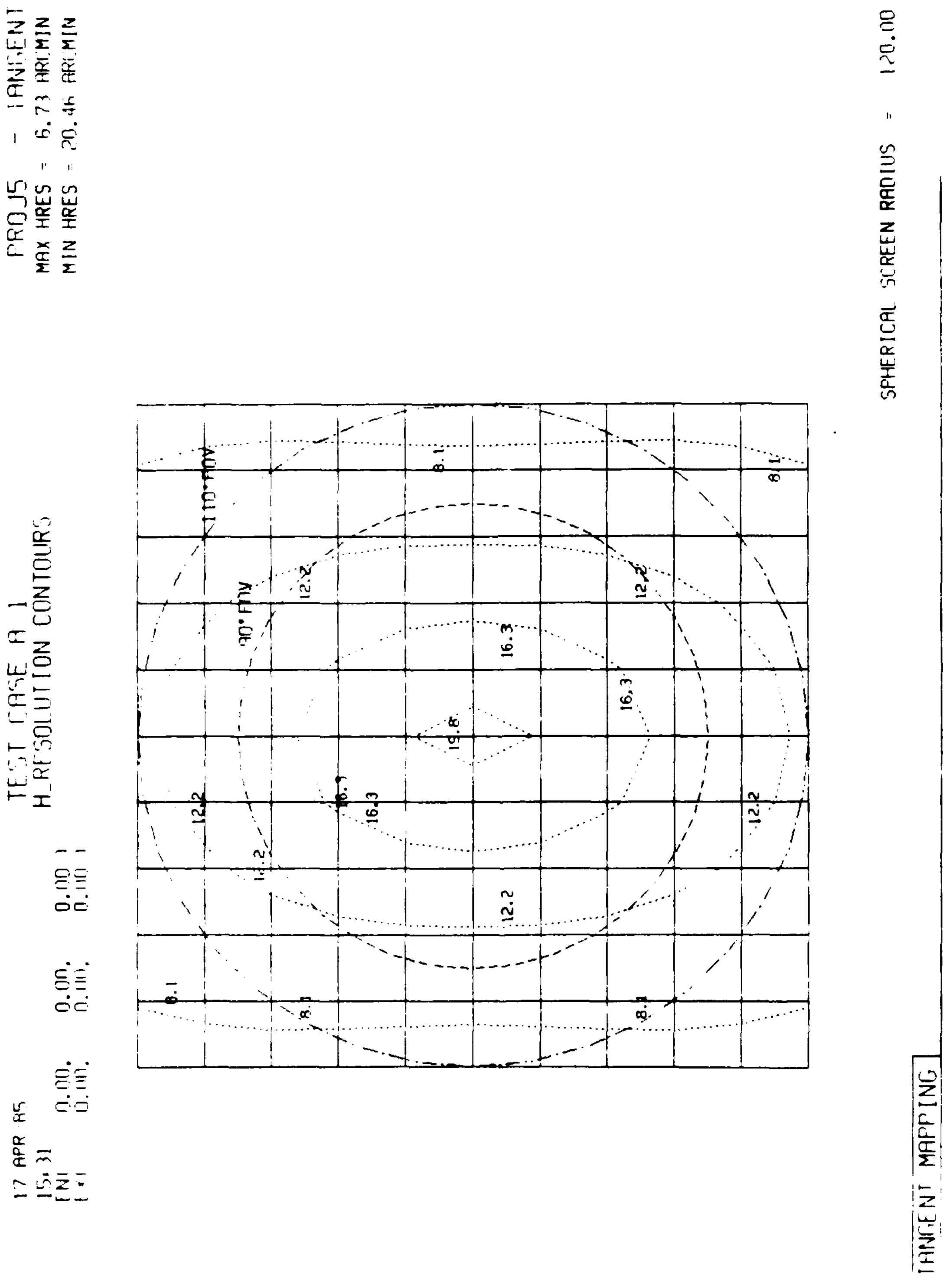
4.3-4. Pole Projectors Distortion Map



4.3-5. Pole Luminance Map



4.3-6a. Pole Vertical Resolution Map



4.3-6b. Pole Horizontal Resolution Map

projection angles (by program default). On axis, the projection angle is zero, and the input intensity value is divided by the distance squared (100 ft.sq.) to give 19.635 FtL. for the on axis luminance. At 45 degrees off-axis projection, the intensity value is multiplied by the cosine of 45 degrees squared (0.4998) and then divided by 100 feet squared to give an approximate 50% falloff in luminance (9.814 FtL.) near the 90 degree FOV circle. The peak luminance values and the location of the 50% contour on top of the 90 degree FOV circle indicate that the graphic outputs are correct.

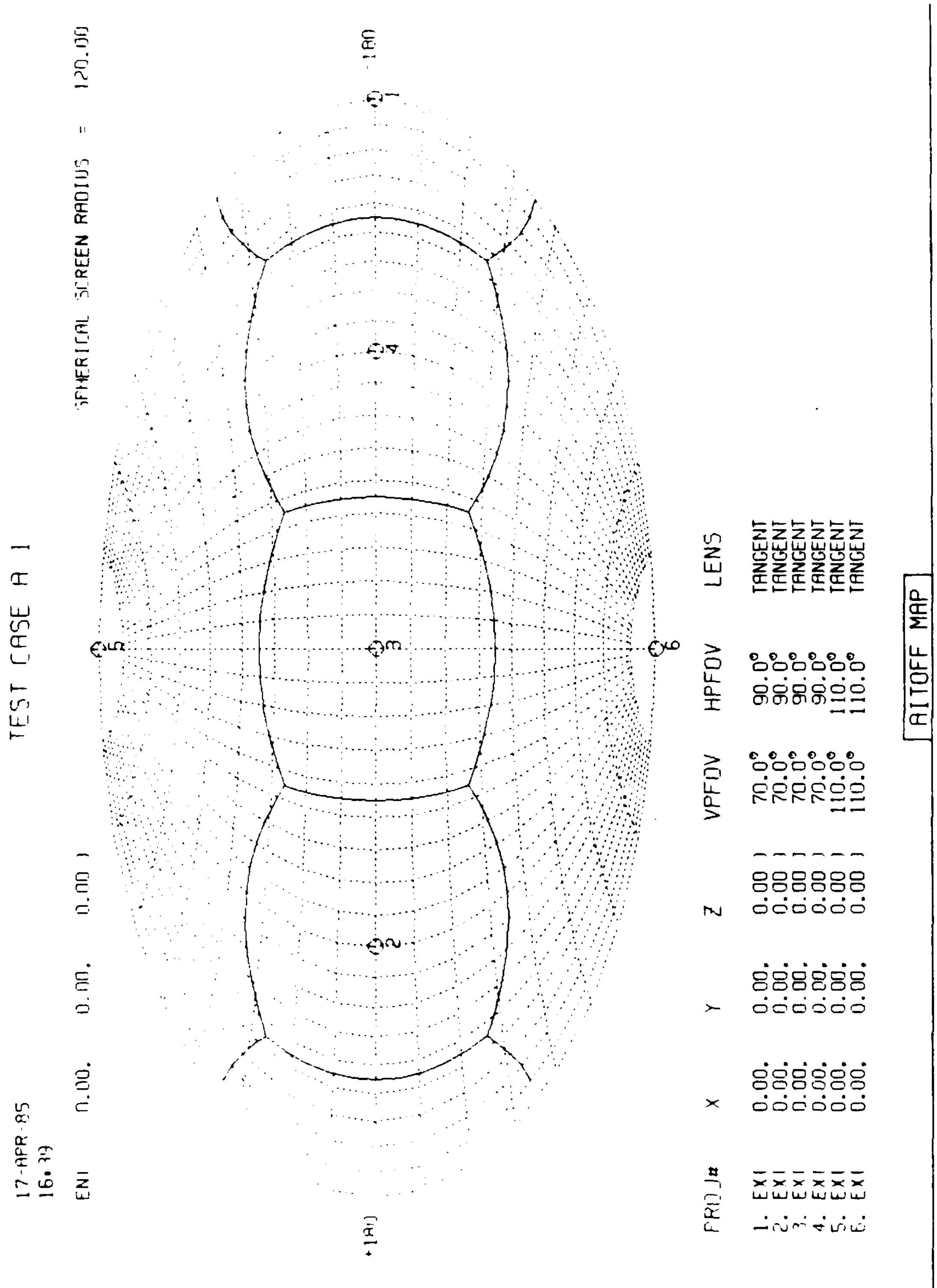
Figures 4.3-6a and 4.3-6b are the vertical and horizontal resolution perspective maps, respectively, for the pole projectors. The number of lines and pixels for the pole projectors is the same as the horizon windows, but due to the larger projection field the pixels are larger and the resulting resolution is less. On Figure 4.3-6a, the maximum vertical resolution is 8.50 arc minutes, while the minimum vertical resolution is 25.84 arc minutes. For the horizontal resolution map, figure 4.3-6b, the maximum horizontal resolution is 6.73 arc minutes and the minimum horizontal resolution is 20.46 arc minutes.

4.3.3 System Aitoff Maps - Figure 4.3-7 is an aitoff map for this test case. The basic aitoff map shows the angular locations of the outlines of the six view windows of this test system. The effects of distortion are shown on the aitoff maps, with additional distortion due to the inherent distortion of the aitoff map as the spherical viewing volume is mapped onto a flat plane for the graph.

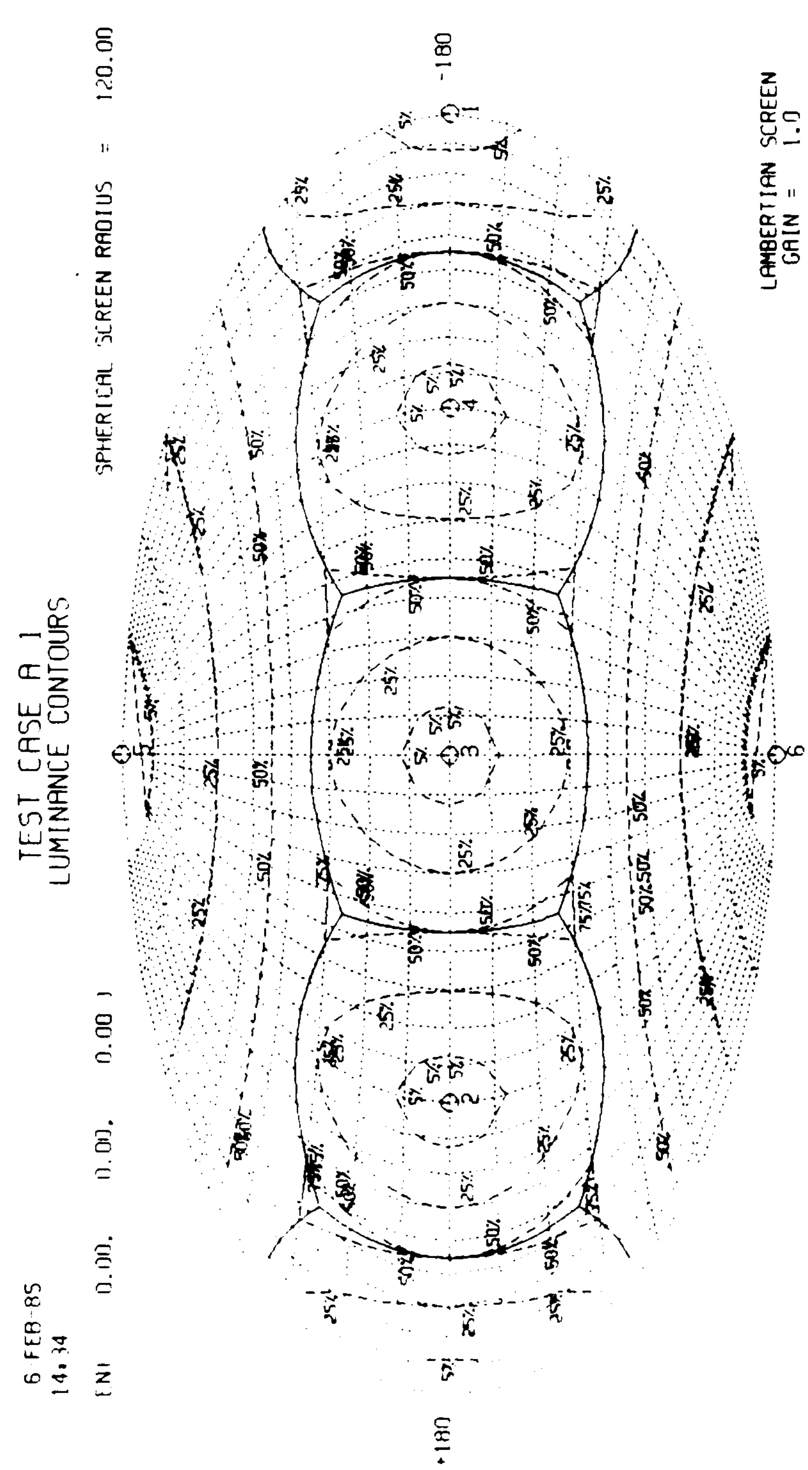
For this system the outlines of adjacent view windows are drawn on top of each other, indicating that there is no gap or overlap between the view window. Since the aitoff map is not continuous across the -180/180 degree horizontal boundary, the view window directly behind the viewpoint (projector #1) is split in half and is drawn on the left and right sides of the aitoff map. The pole view windows also show the effect of the aitoff's discontinuity at 180 degrees.

The aitoff maps contain a major part of the projection system description including: the projection system name, date and time, viewpoint (EN) location, and a table with a description of each projector in the system. The table shows that all projectors are located at the dome origin (0,0,0), and that the horizon projectors (numbers 1 through 4) have projected FOV's of 70 degrees vertical by 90 degrees horizontal. The pole projectors (numbers 5 and 6) are listed as having projected FOV's of 110 degrees vertical by 110 degrees horizontal. When contours are added to the aitoff maps, additional information concerning the luminance or resolution outputs are added to the system description.

The contours on the following aitoff maps are drawn using the same luminance and resolution values from the perspective contours. However the coordinates used in the interpolation process are the aitoff map

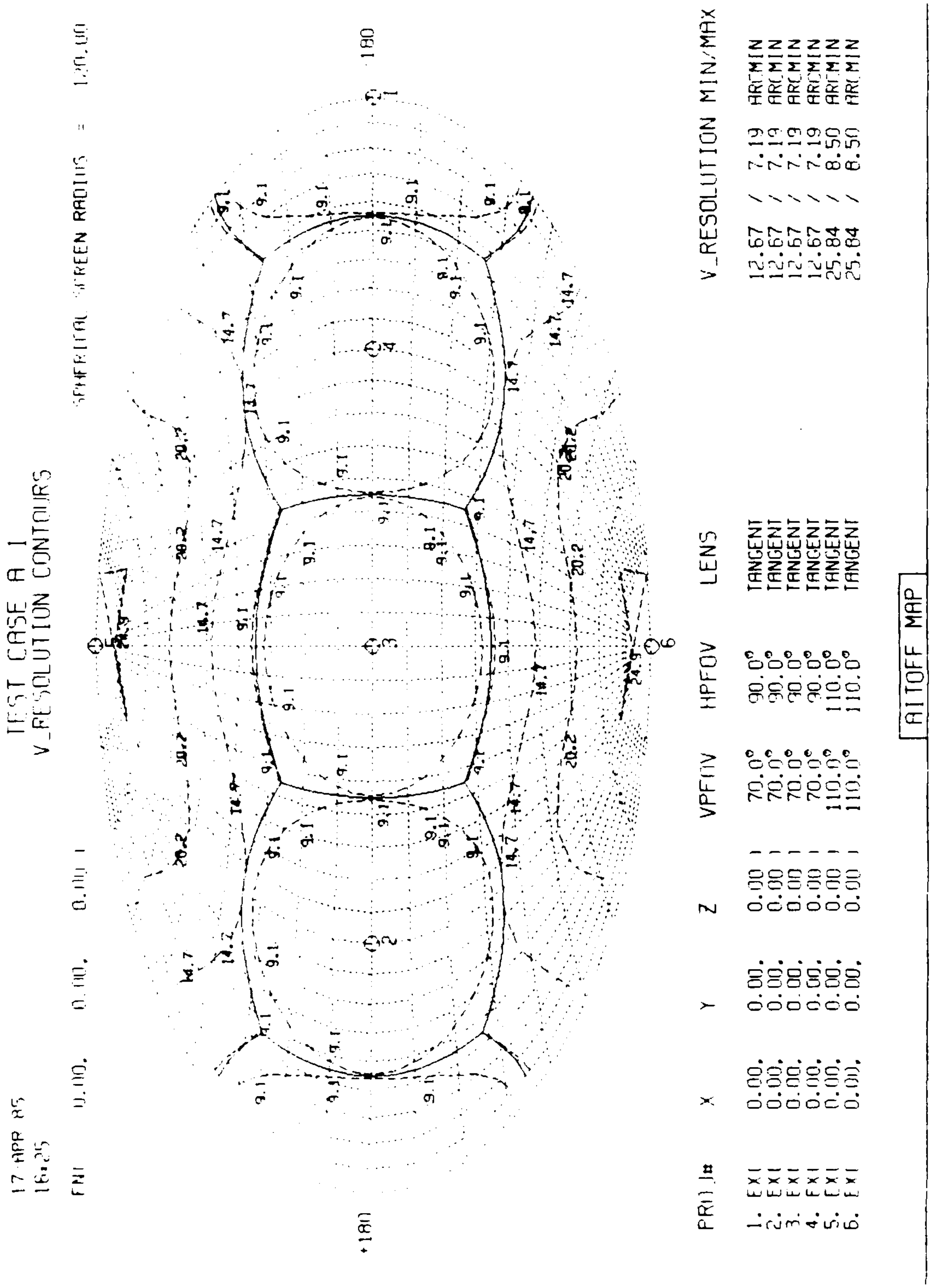


4.3-7. System Aitoff Map

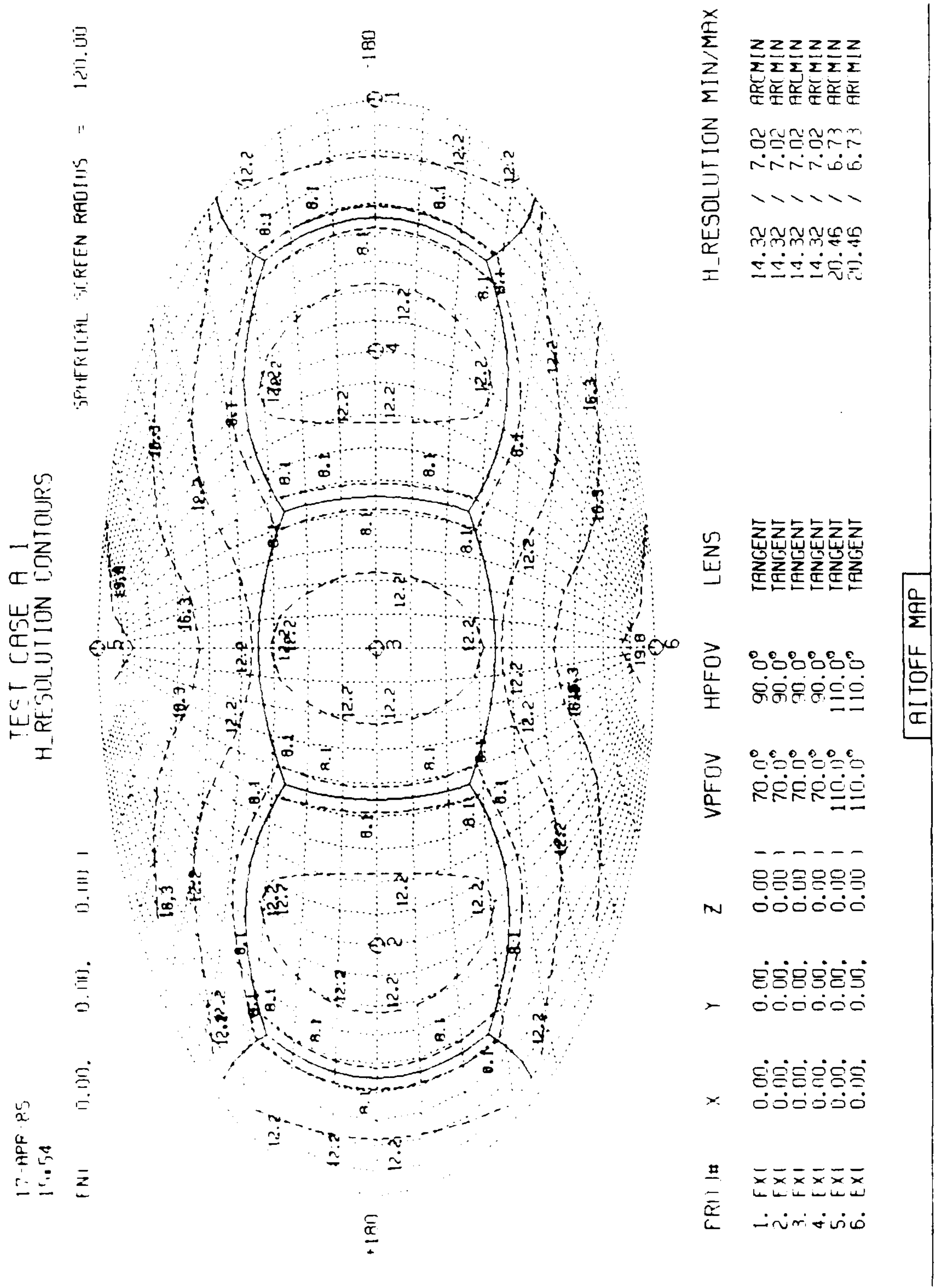


PROJ#	X	Y	Z	VPFOV	HPFOV	LENS	FLUX OUT	LUMINANCE MIN/MAX
1. FXI	0.00,	0.00,	0.00)	70.0°	90.0°	TANGENT	1963.5 CD.	7.885 / 19.635 FTL.
2. FXI	0.00,	0.00,	0.00)	70.0°	90.0°	TANGENT	1963.5 CD.	7.885 / 19.635 FTL.
3. FXI	0.00,	0.00,	0.00)	70.0°	90.0°	TANGENT	1963.5 CD.	7.885 / 19.635 FTL.
4. EXI	0.00,	0.00,	0.00)	70.0°	90.0°	TANGENT	1963.5 CD.	7.885 / 19.635 FTL.
5. FXI	0.00,	0.00,	0.00)	110.0°	110.0°	TANGENT	1963.5 CD.	3.866 / 19.635 FTL.
6. FXI	0.00,	0.00,	0.00)	110.0°	110.0°	TANGENT	1963.5 CD.	3.866 / 19.635 FTL.

4.3-8. System Aitoff Luminance Map



4.3-9a. System Aitoff Vertical Resolution Map



4.3-9b. System Aitoff Horizontal Resolution Map

coordinates and not the view plane coordinates, so the shapes of the contours are different from the perspective map contours.

Figure 4.3-8 is the aitoff luminance map for the test case Since all the view windows have the same peak luminance, the 5% contours are found near the centers of each view window. On the horizon windows, the lowest contour level is the 50% contour which is found near the corners of the view windows as was the case for the horizon perspective maps. The two pole projector view windows have lower contour levels of 75%, which also match the pole view window perspective maps.

Information added to the aitoff map for the luminance contour output includes: the screen gain type and gain value, along with the intensity output and minimum/maximum luminance for each projector in the system. For this system, the screen was specified to be lambertian (with a gain of one), and all projectors have the same intensity output of 1963.5 candelas. For the horizon projectors, the aitoff map shows that the minimum luminance is 7.885 FtL. and the maximum luminance is 19.635 FtL..

Figures 4.3-9a and 4.3-9b show the vertical and horizontal resolution contours. The vertical resolution values for the four horizon windows are listed as 12.67 arc minutes minimum and 7.19 arc minutes maximum on figure 4.3-9a. For the two pole windows, the minimum vertical resolution is listed as 25.84 arc minutes and the maximum vertical resolution is 8.50 arc minutes. The horizontal resolution values, found on figure 4.3-9b are listed as 14.32 arc minutes minimum and 7.02 arc minutes maximum for the four horizon windows, and 20.46 arc minutes minimum 6.73 arc minutes maximum for the two pole projector view windows.

5.0 CONCLUSIONS.

This report documents major parts of the work performed for the Visual Display Parameters (VDP) project. In this project, the use of wide angle display systems was investigated and the knowledge used to model and predict display performance. The model included the ability to define up to six projectors in display systems using spherical or dome screens. The model developed was reduced to a FORTRAN computer program, NVDPMAP, to automate the process of analyzing the display parameters of distortion, luminance and resolution. The actual programs discussed in this report may be obtained by contacting the author.

While the NVDPMAP program does not provide for an exhaustive description of all types of projection parameters, the basic projection model can be modified by those familiar with FORTRAN programming and projection optics. This process is aided by this report describing the theory and the programs that are well commented. If other lens mappings, projector intensity output profiles, screen gain profiles, or parameter calculation methods are desired, these may be included by modifying the subroutines that perform these functions. The basic graphic outputs will

then show the results of the changes made.

The display analysis program, and other programs developed under the VDP project, may be used by running a menu command procedure which simplifies program operation. The use of a formatted input file for the VDPMAP display analysis program provides the benefits of a permanent record of a projector system description and a means to easily enter the data required to operate the program. A master input file, RSMPLDOME.DAT, is stored in the VAX computer and can be edited to insert the parameters of a specific dome display system. This master input file includes a description of all variables as a reminder of the data input required.

By defining a display system for input to the display analysis program, the system performance can be quantified and graphically examined. The effects of changing a system's design may be quickly examined by modifying the input file and running the program again. Examining a proposed system's predicted performance and modifying the design parameters until an acceptable performance is predicted allows the specification of a system design that will provide the desired system characteristics.

APPENDIX A

NVDPMAP INPUT FILE FORMAT

```
LABEL                          !SYSTEM NAME    ( 32 CHARACTERS MAXIMUM )
LGRAPH,LPLUM,LPRES             !LOGICALS FOR PERSPECTIVE GRAPHS (MAP.LUM,RES)
2.,1.,0.3,0.                   !PERSPECTIVE GRAPH DATA(FSCALE,MAG,XBIAS,YBIAS)
LAITOFF,LALUM,LARES            !LOGICALS FOR AITOFF GRAPHS       (MAP,LUM,RES)
Gmax,Gtype                     !SCREEN GAIN AND TYPE                (Gmax,Gtype)
MAPTYPE,DFACTOR                !VIEWPOINT MAPPING TYPE (W/TANGENT DISTORTION)
LTABLE                         !LOGICAL FOR COORDINATE TABLE OUTPUT ( T/F )

R,SCRNTYPE                     !DOME RADIUS, SCREEN TYPE (1-SPHERE,2-CYLINDER)
XE,YE,ZE                       !VIEWPOINT                  EN    - ( X,Y,Z )
NP                             !NUMBER OF PROJECTORS

XPCTR,YPCTR,ZPCTR              !CENTER OF PROJECTOR WINDOW #N PCTR - ( X,Y,Z )
NV,NH                          !# OF VERTICAL AND HORIZONTAL CROSSHATCH LINES
VFOV,HFOV                      !VERTICAL AND HORIZONTAL FIELDS OF VIEW
LINES,PIXELS                   !# OF LINES/PIXELS FOR PROJ RES ANALYSIS
KELLL,KELLP                    !KELL FACTORS FOR LINES & PIXELS ( <= 1.0 )
XP,YP,ZP                       !PROJECTOR #N LOCATION         EX    - ( X,Y,Z )
F,FNUM,LENSTYPE,Tmax           !PROJECTOR LENS #N DESCRIPTION
LCODE,Fmax                     !LUMINANCE CODE, MAXIMUM LUMINANCE OR AXISINT
```

Table A-1. NVDPMAP Input File Format

The above table gives the format of the master input file, RSMPLDOME.DAT, found in the MENU subdirectory. This master file can be edited to create a VDPMAP system input file. The data is arranged in three basic blocks, with each block separated by a blank record (or line). The first block contains the projection system name, logicals for the selection of program output options, screen characteristics, and viewpoint mapping type. The second block contains the dome radius, viewpoint coordinates, and number of projectors. The third block of data is used repeatedly in describing each

of the projectors for the display system. Each record in these three blocks has a brief data description in the comment field to the right of the data field. The comment field boundry is denoted by an exclamation point.

Input requirements for the data for these three blocks is described, record by record, below. The data in the file is read in an unformatted form and must be separated by commas. When entering the data in this file, try to leave the exclamation points in their place, and do not use tabs for spacing. Also, note the placement of commas between variables on a record, and do not remove them from the file.

All variables dealing with lengths should be entered in inches if a luminance analysis is desired. Use of other units will cause incorrect luminance values (would no longer be Foot Lamberts) to be printed on the graphs. These variables include: R, EN, EX, PCTR, and F.

If a luminance analysis is not needed or selected, then dimensional variables could be entered in units that are not inches, as long as they all have the same metric. If the radius is entered in feet, then all 3-D coordinates (viewpoint, projectors, and projected window centers) and dimensional units (lens focal length, etc.) should also be entered in units of feet. If other dimensional units are desired, such as meters or millimeters, just make sure that all dimensional entries are in the same units.

Block one. The first record is for the display system name, LABEL, which is a character variable. Any characters may be used for the name up to a limit of 32 characters. The system name is used as a label for the graphic and table outputs.

The second record of block one is for the logicals which select the perspective graph options of: basic perspective map of each projector view window (LGRAPH), perspective map with luminance contouring (LPLUM), and perspective maps with resolution contouring (LPRES). These perspective maps depict the viewer's true perspective of the projected crosshatch test pattern. If any of the perspective logicals is TRUE, then that perspective output is selected. When FALSE, the graphic output is skipped.

The scaling data for the perspective graphics on the Textronix graphic screen is placed in the third record of block one. Default values are entered in this master file, but they may be changed. There are four real variables for the perspective graphs: FSCALE, MAG, XBIAS, and YBIAS. FSCALE sets the FOV size of the graphic screen for the tangent perspective map according to the equations: VFOV = 2*ARCTAN(FSCALE), and HFOV = 2*ARCTAN(1.2*FSCALE). MAG sets the magnification of the screen. XBIAS and YBIAS are used to set the location of the default screen origin, which allows the positioning of a graph relative the the screen borders. Combinations of FSCALE, MAG, and (XBIAS,YBIAS) will allow the enlargement of subsets of the original perspective map.

The Textronix screen origin is (0.5,0.5) inches from the lower left hand corner of the screen. The screen axes run positive X to the right, and positive Y up. The default values in this master file specify a screen size of just over 126 degrees vertical by 134 degrees horizontal (FSCALE = 2), unit magnification (MAG = 1.0), and a small offset (XBIAS = .3 inches) in the positive X direction. These values will work for most perspective graphs since most view windows subtend less than 134 degrees to a viewer. Reducing FSCALE to 1.0 will set the screen size to 90 degrees vertical by 100 degrees horizontal, and will effectively enlarge the graph produced by the above default values by reducing the FOV size of the screen.

The fourth record of block one contains more logicals, which are for selection of aitoff map output options. As part of the program output, aitoff maps are used to depict the spherical viewing volume surrounding the viewpoint. On the aitoff map, the spherical viewing volume is represented by a set of curved grid lines which indicate spherical viewing angles from the viewpoint. When an aitoff map is selected, each projector's view window outline is drawn on the graph to show the angular placement relative to the viewer. The three logicals, LAITOFF, LALUM, and LALUM, select the basic aitoff map, aitoff map with luminance contouring, and aitoff maps with resolution contouring, respectively. Enter TRUE in the proper variable positions to select these aitoff graphic options.

The screen gain and type, placed in the fifth record of block one, are screen characteristics needed for luminance analysis. GMAX is a real variable for the screen gain value. Three gain types are available, either lambertian, specular/diffuse, or retro-reflective, by entering an integer 1, 2, or 3, respectively, in the GTYPE location. A discussion of screen gain can be found in reference 2.

In the sixth record of block one, specification of the viewpoint mapping type for the perspective graphs is made. The selection determines the method of transforming the 3-D coordinates of viewed patterns, relative to the viewpoint, onto the plane of the graphic screen. Four options exist: tangent, theta, sine, and tangent with primary distortion. The tangent mapping gives a true perspective view (no distortion), while the other options distort the perspective view. For the purposes of providing true perspective graphs of the view windows, MAPTYPE is set to an integer 1, which selects a tangent perspective map. If the other optional viewpoint mapping types are desired, enter an integer 2, 3, or 4 for the theta, sine, or tangent with primary distortion options, respectively. If tangent with primary distortion is selected, a coefficient for the primary distortion term is required. Enter zero for the coefficient if the other options are chosen.

The last record in block one, record seven, contains a logical variable for the option for the file output of tables with the 2-D and 3-D coordinates of the both the projected pattern and the viewed pattern. When LTABLE is true, subroutine OUTPUT is called which opens two data files, VIEW.DAT and PROJ.DAT. Information relative to the projection system is first placed into both output files. In file PROJ.DAT, this information is

followed by the 2-D coordinates of of the pattern on the projector Front Focal Plane (FFP) and the 3-D coordinates of the pattern after projection onto the screen. Data file VIEW.DAT contains the perspective 2-D coordinates of the projected pattern on the View Plane positioned in front of the viewer and the 2-D coordinates of the input pattern scaled to the same height as the perspective pattern. The coordinates in these files will have the same metric as the dimensional variables used to specify the projector system. These output files can be used for further analysis of the graphic output and are also useful for debugging the main program.

Block two. Record one of block two should contain the screen radius value, R, a real variable, and a screen type descriptor, SCRNTYPE, which is an integer. R should be entered in inches. SCRNTYPE can specify either a spherical (1) or cylindrical (2) screen. The spherical screen selection and resulting outputs have been experimentally verified, while the cylindrical screen selection has not been fully verified.

The second record contains the 3-D coordinate of the viewpoint location, EN, relative to the dome screen origin. EN should also be entered in units of inches. The third record in block two has the integer number of projectors, NP, in the system. NP is used as a counter for the data input of the NP projectors in the system, so there should be NP projector descriptions (block 3 data) following block two. If a projector description block, or individual records of any block, are missing from the input file, an error will occur and the program will abort.

Block three. Block three is repeated for each projector in the system. A blank record is placed between each projector block. The first record in the block specifies the 3-D screen intercept, PCTR, for the optical axis of the projector. PCTR, combined with the projector exit pupil location EX (in record 6), defines the orientation of the projector by specifying the origin and screen terminus of the optical axis. The intercept coordinates are real variables, and are specified relative to the screen origin in inches. Since the PCTR coordinates are screen intercepts, they should define points that lie on the screen surface. A program, SPPT.FOR, is in the VDP menu to assist in finding the 3-D screen intercept coordinates by using sherical angles from the exit pupil toward the screen surface.

The crosshatch test pattern to be projected is specified by records two and three of the projector block. Record two contains the integer number of vertical, NV, and horizontal, NH, crosshatch intersections in the pattern. Due to the size of the data storage arrays, NV and NH are limited by the relation: NV * NH <= 1000 . The maximum square crosshatch is then a 31 by 31 pattern. Record three finishes the pattern description by specifying the vertical and horizontal FOV's projected, VFOV and HFOV, from the exit pupil. The FOV's are limited to values less than 180 degrees (+- 90 degrees) for a tangent or sine mapping, and less than 360 degrees (+-180 degrees) for a theta map. VFOV and HFOV are real variables for the angular height and width through the center of the projected test pattern. The size of the projection plane is found from the lens focal length F, the VFOV and HFOV, and the lens mapping equation (specified by LENSTYPE).

Records four and five contain information concerning the resolution on the projection plane. Record four contains the number of LINES and PIXELS that make up the video image to be projected. The variables in the fifth record, KELLL and KELLP, account for the spacing between the lines and pixels by reducing the pixel height and width (KELLL and KELLP should not be greater that 1.0. The pixel sizing depends on these four variables, LINES and PIXELS, KELLL and KELLP, and the initial projection plane size (as determined from VFOV, HFOV, LENSTYPE, and F). The pixels are projected onto the screen as part of the resolution analysis. See section 2.6 for more information on pixel projections.

The 3-D coordinates for the location of the projector exit pupils EX, (XP,YP,ZP), are listed in record six of each projection block. Again, these coordinates are specified relative to the dome screen origin and should always be in units of inches. Projectors should be located inside the dome.

Record seven contains information about the lens of the projector. This includes the lens focal length (F), the f/# (FNUM), lens mapping type (LENSTYPE), and lens transmission (T). F, FNUM, and T are real variables, where T should be equal to or less than unity. LENSTYPE is an integer which selects the option of a tangent projection lens (LENSTYPE = 1), or a theta projection lens (LENSTYPE = 2). The tangent map does not distort the crosshatch pattern when projected, while the theta map gives a barrel distortion to the pattern.

The last record in the projector description block is information for use in performing the luminance analysis. LCODE is an integer which selects one of the two illuminance methods listed in section 2.5. When LCODE = 1, the lens effect method will be used, and FMAX should contain the maximum luminance, in Ft.Lamberts, on the projection plane. If LCODE = 2, the intensity output method will be used, and the axial intensity value at the exit pupil, in candelas (lumens per steradian), should be entered for FMAX.

APPENDIX B

MEASUREMENT OF SCREEN GAIN PROFILE

Use of an alternate screen gain in NVDPMAP requires that Gmax be entered into the dome input file, and that $g(\Theta g)$ be inserted into the luminance subroutine LUMVAR in place of the default gain profile. Alternately, Gmax can be set to unity, and both Gmax and $g(\Theta g)$ can be inserted into LUMVAR as a single function. The gain profile could be obtained from the manufacturer, or may need to be experimentally measured to obtain the maximum gain and gain profile.

One method of measuring a screen sample requires the use of a light source, a Lambertian surface, luminance photometer, and a means to measure angles from the screen sample normal. A 35mm projector works well as a light source, and a Lambertian surface (Magnesium Oxide) can be obtained from companies specializing in photometric equipment. A block of Magnesium Carbonate is a much cheaper substitute which approximates a lambertian surface. Any luminance photometer can be used, which, because luminance is independent of viewing distance, removes the need for distance measurements between the sample and photometer.

Mount the screen sample and lambertian surface in a suitable small holder, and set the light source to illuminate the sample along its normal. To measure the luminance at angles from the sample normal, mark off incremental angles in a rough arc centered at the sample. Start at the light source and move around the arc towards a point 90 degrees from the sample normal. The size of the increments depends on the intended viewing angle range and the shape of the gain profile.

At the predetermined angle increments along the arc, measure and record the luminances on both the screen sample and lambertian surface (taking care to fill the photometer measurement aperture completely). The ratio of the sample luminance over the lambertian luminance provides the data for finding Gmax and $g(\Theta g)$. The maximum luminance ratio is used for Gmax, which

should be found at zero degrees from the screen sample normal. The remaining luminance ratios are then divided by Gmax and used in finding the $g(\Theta g)$ function. Note that the computer program expects Θg to be in radians, so $g(\Theta g)$ should also use angles in radians.

The luminance on the lambertian surface is used to remove the variations in the light source output. To simplify calculations, an aperture on the light source can be used to reduce the luminance reading on the lambertian surface to one Foot Lambert. The luminance readings on the sample surface are then equal to the gain value at that angle.

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